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November 24, 1992

MEMORANDUM

TO: Distribution

FROM: Takeshi Yoshihara
Deputy Director

SUBJECT: DISTRIBUTION OF "ANNUAL REPORT: GEOTHERMAL RESOURCES ASSESSMENT", SEPTEMBER 1992

I am pleased to provide you with, for your information and reference, a copy of the subject report which was prepared for DBED by GeothermEx, Inc.

TYoshihara

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ANNUAL REPORT:

GEOTHERMAL RESOURCES ASSESSMENT

for

DEPARTMENT OF BUSINESS ECONOMIC DEVELOPMENT & TOURISM

Honolulu, Hawaii

by

GeothermEx, Inc.
Richmond, California

SEPTEMBER 1992

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1. EXECUTIVE SUMMARY

GeothermEx, Inc., has been contracted by the Department of Business and Economic Development (DBED) to provide consulting services related to development of the geothermal resources of Hawaii, principally at the Kilauea East Rift Zone (KERZ), of the Puna District of the County of Hawaii. These services include preparation of an Annual Report. The present report, based on the initial 12 months of work, contains a description of information sources, a review of the status of exploration and drilling, and analysis of well-test results, a conceptual model of the geothermal resource, an estimation of geothermal reserves of the KERZ, discussion of the potential development impacts, and recommendations for obtaining additional data.

Geothermal resources have been investigated by geological, geophysical and geochemical surveys on all the Hawaiian Islands. The results of these surveys were evaluated by a State committee in 1984. The resulting Statewide Geothermal Resource Assessment identified Potential Geothermal Resources Areas based upon selected criteria. The only area for which drilling information existed was, and remains, the KERZ. The geothermal reservoir identified there is the principal subject of this report.

The results of reconnaissance exploration elsewhere in the State of Hawaii have been reviewed and are summarized in this report. Our review is perhaps more conservative than prior presentations in its estimate of the probability of finding a high-temperature resource other than on the Island of Hawaii. Kauai, Oahu and Molokai are estimated to have less than 5% probability for finding a commercial high temperature resource; Lanai has less than 10% probability; and Maui has less than

20% probability of finding a high temperature commercial resource. Hawaii has from greater than 50% to less than 10% probability of finding commercial high temperature resources at other locations from the KERZ.

Fourteen deep holes have been drilled into the KERZ, nine of which have proven the Puna geothermal reservoir. Hot water and steam at temperatures as high as 680°F exist in a reservoir lying at depths between 4,000 and more than 7,000 feet. The Puna reservoir is one of the two or three hottest in the United States.

The field discovery well HGP-A was drilled on behalf of the State of Hawaii in 1976, and supplied a 3 MW demonstration power plant from 1982 to 1989. Three other wells (Ashida 1, Lanipuna 1 and Lanipuna 6) were drilled at the margins of the known reservoir area by Barnwell Industries between 1981 and 1984. These wells were unproductive, but they provided valuable subsurface temperature and geologic information, and one of them (Lanipuna 6) may be usable as an injection well.

Three wells were drilled and flow tested by Thermal Power Company between 1981 and 1985 (Kapoho State 1, 2 and 1A). All three were tested as production wells, and were considered to be capable of producing 2 to 3.2 MW each. All have had casing damage; only KS-1A may still be usable as an injection well.

This casing damage has been attributed to one of three causes: poor cementing in lost-circulation zones; casing degradation resulting from unsuitable choice of casing; or parting of the casing at the buttress-threaded casing-joint connections. The mechanical problems of the Thermal Power wells provide the basis for establishing standards for the design and drilling of future wells.

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During 1990-1991, the Puna Geothermal Venture (PGV), a successor-in-interest to Thermal Power, drilled three development wells, KS-3, -7 and -8. The detailed technical data from these wells are not yet public. All three wells intercepted potentially productive targets in the geothermal reservoir. Well KS-3 is completed as a production well but may be converted into an injection well.

Well KS-7 was drilled as an injection well, but intercepted high pressure steam and gas at less than 2,000 feet in depth, and has been plugged back. The casing program of KS-7 was insufficient to allow conversion for production. Well KS-8 found high-pressure steam and gas at about 3,400 feet in depth; however, a blowout and uncontrolled release of H_2S caused State and County agencies to suspend exploration and development permits in June 1991. Some remedial work, including cleanout to the top of a cement plug and cementing of 5-inch-diameter casing-patches over damaged casing, were done in early 1992; further rework operations have been authorized as of the date of this report.

A tenth deep well, True-Mid Pacific KMERZ A-1, was drilled several miles to the west, between 1989 and 1991. A total of 5 legs were drilled, several of which reportedly encountered high temperatures and some steam entries. Very little data are available publicly from this well.

Three deep slim holes (SOH-1, -2 and -4) were core drilled as part of the State's Scientific Observation Hole (SOH) program in 1990-1991. The holes successfully proved that high temperatures occur for at least 1,500 feet northward from discovery well HGP-A, as well as for several miles southwestward and northeastward from well HGP-A. The SOH holes were not permitted for flow testing. Injection tests indicate low

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permeability in the high-temperature parts of the holes, except for one zone in SOH-2.

The State's future drilling programs would more effectively assess geothermal reservoirs with rotary-drilled rather then cored medium-size diameter (5-7/8") wells. Design of the wells should follow the same criteria as for production wells, to safely flow test reservoir fluids. Application for permits to flow test the wells should be pursued.

Publicly available surface and subsurface data have been examined to develop a conceptual hydrogeologic model of the Puna reservoir. Subsurface temperature and pressure data indicate that thermal fluid is being channeled along steeply dipping structures generally paralleling the NE-trending KERZ and the 1955 eruption fissure within the KERZ. Temperatures appear to be developed symmetrically on both sides of the fissure. The resulting temperature pattern suggests that a horizontal component of flow is directed from SW to NE parallel to the trend of the KERZ. A strong horizontal pressure gradient parallels the temperature gradient, indicating relatively poor horizontal permeability in the NW-SE direction, and further supports the conclusion that flow is dominated by steep NE-trending structures.

Based on the structure of older rift zones exposed elsewhere in the Hawaiian Islands, it is probable that high-permeability zones are related to fracturing during dike emplacement. The dikes, which fill the rift zones, are individually from about one foot to tens of feet wide, dip from 90° to 70° and, in densely intruded areas, occur in clusters or are spaced only a few feet apart.

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Hydrological studies and chemical analyses of fluids produced from the deep Puna wells indicate that the thermal fluid is a mixture of fresh water and seawater, with the seawater component apparently increasing to the SE, away from the fissure zone. This suggests that recharge to the system may be mainly meteoric in origin.

Although various warm springs occur along the coast southeast of the drilled area, the absence of fumaroles or large hot springs indicates that the system does not discharge significantly at the surface. There may be major discharge in the subsurface, perhaps into the sea. The basal ground-water level is just above sea level, and an early exploration well found near-boiling temperatures at sea level immediately northeast of the drilled area. The thin high-temperature zone penetrated by the early exploration well suggests that there is a lateral discharge of thermal fluid on top of the local cold-water table.

Based on the conceptual model developed in this report, three different categories of geothermal development areas can be defined within the Puna district with varying degrees of certainty concerning their resource potential. The three areas are referred to in this report as proven, probable and possible in a decreasing order of certainty.

The proven resource area, defined by successful production wells drilled to date, is estimated to be about 0.6 to 0.9 square miles in area. The probable resource area, defined by the additional information from SOH wells, which were not flow-tested, is estimated by analysis of temperature data and conservative geological extrapolation of the drilling results to be 6 to 12 square miles in area. The possible resource area, defined by geological extrapolation, is estimated at 10 to 20 square miles in area.

The most-likely reserves of geothermal energy within these areas are calculated by probabilistic methods to be respectively: 21 MW for the proven area, 141 MW for the probable area, and 157 MW for the possible area. Another estimate of reserves by GeothermEx, using different methodology relying primarily on slim hole data, provided results consistent with those of this report. Further numerical simulation will benefit greatly from detailed results of testing KS-3, KS-8 and KMERZ A-1. Reserves of an area may only be economical to develop if commercially acceptable well productivity can be demonstrated.

Well HGP-A supplied a 3 MW power plant from 1982 to 1989. During a flow test in August 1982, it was demonstrated that well KS-1 was capable of producing 3.2 MW. Well KS-2's productivity during August 1982 was estimated to be only 1.0 MW; however, the casing was found to have been damaged during this test, constricting the flow from the well. The October 1985 well test data from well KS-1A indicated that the well also is capable of producing approximately 3.2 MW. Very fragmentary data from KMERZ A-1 suggest also a power output equal to about 2 or 3 MW. Data are awaited from the KS-3, -7 and -8 wells. Early estimates of capacity are higher than for the KS-1 and -1A wells.

PGV originally estimated that as many as eight production wells, with productivity of about 3 to 3.5 MW each, would be required in order to supply steam to a 25 MW (net) power plant. It is speculated that wells such as KS-8 may produce as much as 10 MW each, drastically reducing the number of wells needed to supply the plant, if wells can be drilled and operated safely and correctly.

The injection requirement for the 25 MW (net) development is estimated to be approximately 1,400 gallons per minute. Two injection

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wells are expected to be sufficient to dispose of all wastewater and non-condensible gases from the power plant. PGV intends to drill two additional injection wells and keep one more on stand-by.

Non-condensible gases are to be reinjected into the reservoir. If so, sufficient injection water flow must be provided. Injection of non-condensible gas into the reservoir carries the risk of gas breakthrough at the production wells. Because of the relatively high H_2S/steam ratio at Puna, the condenser and injection system must be sealed thoroughly, to avoid corrosion caused by the intrusion of oxygen from the atmosphere.

There are three risks associated with corrosion. The first is mentioned above and is mitigated by maintaining an oxygen-free environment in critical parts of the brine system. The second is caused by external attack on cement and casings from corrosive ground-water; well casings have been designed to mitigate this problem. The third risk is that steam corrosivity may increase with time, due to the presence of volatilized hydrochloric acid in superheated steam. Should this occur, caustic would have to be injected into the steam flow to neutralize the acid.

Geothermal exploration is presently at a near-standstill in Hawaii. The State's SOH drilling program, also has been halted. However, the SOH cores are now being organized for geological, geochemical and geophysical laboratory studies. Reports are in progress summarizing the initial lithologic studies of the three holes and consolidating the injection reports into a single reservoir engineering report.

PGV has had some success in getting its operating permits reinstated, with the emplacement of various new standards and conditions for operations. PGV now will rework KS-8, and test it for production, then workover and test wells KS-1A and KS-3 for injection. Based on the results of these operations, PGV will drill the additional production and injection wells necessary to operate its power plant.

The other active operator, True/Mid-Pacific Geothermal Venture, has suspended activity in order to obtain additional permits.

The State would be greatly benefitted by expediting acquisition of all relevant data from well drilling, logging and testing by operators. The operators also should provide complete documentation explaining methods of data collection and analysis.

Other exploration techniques that the State may consider useful to help illuminate the structure of the geothermal reservoir are self-potential (SP) surveys over selected areas, detailed spatial analyses of seismicity data, airborne EM/VLF mapping, selective resistivity soundings where gaps in old surveys remain, and gravity profiling. This will enable the State, through its agencies and consultants, to provide wise and timely regulation and management of the geothermal resources of Hawaii.

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2. INTRODUCTION

2.1 Purpose and Scope

GeothermEx, Inc., has been contracted by the Department of Business and Economic Development (DBED) to provide consulting services relating to the development of the geothermal resources of Hawaii. These services include preparation of an annual report. Principal efforts have gone into the assessment of the Kilauea East Rift Zone (KERZ) of the Island of Hawaii (figure 2.1). This report presents the results of the initial twelve months of work on the project. It consists of:

- a discussion and analysis of the information available to this project;
- an evaluation of the results of geological, geophysical and geochemical surveys, principally in the KERZ;
- a review of the current status of geothermal exploration and development, and the results of drilling, on the Island of Hawaii;
- a description of the conceptual hydrogeologic model of the KERZ geothermal system, developed for this project;
- an evaluation of the extent and characteristics of the KERZ geothermal resource;

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- a discussion of the methodology for numerical modeling of the KERZ geothermal reservoir;

- a discussion of potential resource impacts and risks;

- design and engineering recommendations for geothermal wells;

- a summary of the statewide geothermal resource assessment program; and

- recommendations for continued work.

In Chapter 2.2 and 2.3, information sources are described and evaluated, and methodology is discussed. Chapter 3 contains a review and analysis of previous surface exploration. In Chapter 4, the results of drilling and well testing are discussed. From these, a conceptual hydrogeological model of the geothermal system is developed and presented in Chapter 5. Chapter 6 contains a quantitative evaluation of the resource, including an assessment of available well-test and production data, and a provisional estimate of the reserves within the KERZ.

Chapter 7 presents a detailed discussion of the impacts and possible risks associated with development of the geothermal resource. This includes a commentary on drilling practices and related engineering considerations. Chapter 8 presents the methodology of numerical modeling to be applied to the KERZ. In Chapter 9, the status of the statewide geothermal resource assessment is reviewed.

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Selected references to all of the above are given in Chapter 10. Tables, figures and appendices provide illustrations and documentation of these findings and recommendations.

Many prior reports have presented fragmentary descriptions of the resource as determined from specific exploration techniques, such as geophysical surveys, geochemical analyses, and volcanological analysis. Other reports, such as those by ENEL (1990) and Thomas (1986), have catalogued and reviewed existing surveys and made recommendations for further work. By contrast, the present report presents an integrated analysis of data from deep wells and from surface exploration, from which is constructed a realistic model of the geothermal system. From this, the extent and quantity of the geothermal resource has been calculated on a provisional basis.

2.2 Sources of Information

Surface exploration has been conducted and reported by a large number of investigators (see Chapters 3 and 11). Pertinent data have been taken from these sources for use in construction of the conceptual model. However, as mentioned above, the model and the estimate of reserves are based on the integration of subsurface and surface data.

Subsurface data for the KERZ geothermal resources come from a variety of sources. One primary source is the wells drilled by Thermal Power Company, providing data on drilling, lithology, downhole temperature and pressure, fluid chemistry and well-test results. These data, originally proprietary to Thermal Power Company, have now become public information under terms of State of Hawaii regulations.

Data from Barnwell Industries' Ashida and Lanipuna wells, similar to the Thermal Power Company data suite described above, have also been used for this study. These data were submitted by Barnwell to the State of Hawaii, and therefore also are in the public domain. A variety of useful data from the HGP-A well and demonstration power plant have been published since the well was drilled in 1976; these also were used in our analysis.

During 1990-91, data became available from the State of Hawaii Scientific Observation Hole (SOH) wells. This includes drilling information, lithologic data from the cores, downhole temperatures, and injection-test results. GeothermEx was contracted by the Hawaii Natural Energy Institute (HNEI) and Electric Power Research Institute (EPRI) to design and conduct the injection tests, and to collect, process and interpret the test data. As part of this project for DBED, GeothermEx also has examined the cores and reviewed the geological interpretations of the HNEI investigators.

In 1991, information was received relative to the results of the drilling and logging of wells KS-3, -7 and -8 by Puna Geothermal Venture (PGV), an entity formed by OESI Power Corporation, the successor-in-interest to Thermal Power Company. Most of this information still is confidential, and therefore is not included herein; however, our knowledge of the characteristics of those wells has added to our understanding of the geothermal system, and has helped shape our views on developmental impacts. Further commentary must await release of results by the developer.

In June 1992, limited information was received from the Department of Land and Natural Resources (DLNR) regarding the True-Mid Pacific Geothermal Energy Company well KMERZ A-1. This information included mud logs from the original hole, as well as from its Sidetrack 1 and Redrills 2, 3 and 4. Some temperature and spinner logs and morning drilling reports were included. Significant items which were not received include directional surveys, flowing temperatures and pressures, and chemical analyses of water and steam produced from the well. It is unclear from the available data what volumes of fluid were produced.

2.3 Methodology

All of the available surface and subsurface data have been reviewed in detail, and then processed, plotted and analyzed, to provide the best estimates of the major characteristics of the Puna geothermal system of the KERZ. These are:

- geologic structure and lithology;
- temperature, pressure and permeability distributions in three dimensions;
- fluid chemistry; and
- fluid flow paths.

These characteristics then were used to construct a 3-dimensional conceptual model of the KERZ. This conceptual model has been used to identify the major zone of upflow of the geothermal fluid, and to provide probable physical boundaries and flow constraints for the geothermal system. Data of fluid chemistry are used to define pathways of inflow of fresh and/or saline water into the geothermal system, and to estimate the degree of fluid mixing.

Well-test data have then been used to determine well deliverability and injectability. This has provided an initial indication of probable reservoir behavior under production conditions.

The KERZ has then been divided into three segments, based on the availability and quality of surface and subsurface information. From all of this, and applying probability theory to the calculated reservoir dimensions and its temperature distribution, provisional values of the geothermal resource have been derived numerically for the three sub-areas. Categories of proven, probable and possible resource have been established, and estimates made for each category.

Additional and better well-test data are needed. It is assumed that further data will be forthcoming from both the PGV and True Geothermal projects.

The next step in quantification of the resource is numerical simulation, based on the matching of initial state conditions. This is described further in Chapter 8.

3. HISTORY AND RESULTS OF SURFACE EXPLORATION IN THE KERZ

The KERZ has been studied repeatedly by a large number of investigators, over a long period of time, using a wide variety of surface exploration and analytical techniques. The objectives of this intensive and widespread exploration activity have not necessarily been related to geothermal resource assessment or development. Indeed, many of the surveys have been concerned with such topics as: determination of the physical properties of magma chambers; the evaluation of potable groundwater resources; compilation of regional geological or geophysical maps, as part of regional mapping studies; research into active volcanic processes; evaluation of the seismicity of an active volcanic rift; identification of pre-eruption earthquake signatures; determination of the sequences of hydrothermal mineral deposition in volcanic rock suites; research into gas emissions from active volcanic systems; etc.

Government-funded geophysical surveys carried out over the KERZ during the 1970s included gravity, magnetic, seismic, and a variety of electrical surveys, including DC resistivity (bipole-dipole and pole-dipole), EM (time domain, variable-frequency inductive soundings and transient soundings), *mise-à-la-masse* and SP (self-potential, detection of electrical streaming potentials).

Despite their varied origin, many of these research studies have been applied in geothermal exploration or characterization of the KERZ. Not surprisingly, the results have been highly variable in utility, reflecting such factors as the area(s) of coverage, the scale at which work has been done, and the ultimate purpose of the work. Chapter 11 presents a detailed bibliography of source works utilized in this report; reference is given there to most of the geological,

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geophysical and geochemical studies made across the KERZ in the past two decades, unless their purpose has been barely marginal to the objectives of this report.

Of the many geophysical anomalies defined by these surveys, SP anomalies appear to be most closely associated with geothermal features, both in the Kilauea crater area, and in the KERZ. Indeed, the discovery well of the Puna field (HGP-A) was sited in part on the basis of a large SP anomaly located north of the Puulena Craters (figure 3.1). The hole was not sited directly on the anomaly because a lease for an appropriate site could not be obtained. A subsequent well, Lanipuna 1, sited on the anomaly, was hot but dry.

An aeromagnetic survey of the KERZ was published by the U.S. Geological Survey in 1986 (Map MF-1845-A). The survey shows a major discontinuity in magnetic anomalies corresponding to the location of a possible NW-trending fault that cross-cuts the KERZ. Assuming that the area of offset is a prospective zone of future development, however, the resolution of the magnetic survey is insufficient for selecting specific drilling targets.

An aeromagnetic survey near well HGP-A and a modeling study of the aeromagnetic data was commissioned by Thermal Power. The results indicated that a controlled source audiomagnetotelluric (CSAMT) survey would be able to delineate the reservoir. Thermal Power commissioned a CSAMT, but because electrode-contact resistance was much higher than the contractor had anticipated, it was not possible to complete the first phase of the survey according to specifications. In addition, based on the limited data that the contractor was able to gather, it appeared that the CSAMT method would not be able to delineate closely and

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unequivocally the limits of the reservoir. In view of these problems, the survey was abandoned.

The anomaly most-closely associated with the surface trace of the main eruptive fissure zone shown in figure 3.1 is a chemical anomaly caused by the concentration of mercury in near-surface soil samples. Again, as with the aeromagnetic anomaly, this anomaly shows the NW-trending discontinuity near HGP-A; this discontinuity was presumed to be caused by a fault offsetting the rift trend. The highest concentrations of soil mercury, however, are not in the area of offset, but over the NE-trending fissure just to the northeast of the presently drilled area.

In summary, the geophysical and geochemical surveys completed in the KERZ show several anomalies. However, these anomalies do not coincide with each other in area, and therefore cannot be used with confidence to delineate the reservoir; nor do they have sufficient resolution to be useful for well siting. Additional geophysical surveys are not recommended for well siting but may be useful for further structural analysis.

Of the wide suite of surface exploration techniques, the most useful in the selection of targets and siting of wells, and in characterization of the geothermal system, have been:

- detailed surface geologic mapping, including photogeology; and

- geochemical analysis of spring and well waters, fumarole gases, and steam separated from fumaroles and deep well waters.

Also interesting, but not of demonstrated use in the selection of well sites, are:

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- geochemical analyses of soil gases;

- detailed gravimetry, especially regarding the identification of regional and local structures;

- self-potential (SP) electrical surveys; and

- passive monitoring of microearthquake seismicity.

More ambiguous, or of somewhat lesser value in geothermal exploration, have been:

- airborne mapping of very-low-frequency electromagnetic anomalies (EM/VLF);

- electric resistivity soundings and surveys based on various electrode configurations and techniques (bipole-dipole, Schlumberger, mise-a-la-masse, etc.);

- time-domain electromagnetic (TDEM) surveys; and

- airborne magnetic surveys.

The application of these techniques in conceptual modeling of the KERZ is presented in Chapter 5.

3.1 Geophysical Surveys

Homogeneous coverage of the KERZ is afforded by only three kinds of geophysical data: passive seismic, aeromagnetic, and airborne very low-frequency electromagnetic (EM/VLF). Other types of data,

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including ground-based geoelectrical, gravimetric, microearthquake and ground noise, have been collected intensively in the lower KERZ, east of Pahoa; however, these data are virtually non-existent for the middle and upper parts of the KERZ. Even within the lower KERZ, however, the distribution of observation points has been very uneven; station positions apparently have been confined to the irregular, mostly sparse, distribution of roads.

3.1.1 Gravity Surveys

A Bouguer gravity anomaly map that covers the entire island of Hawaii has been prepared (Kinoshita, 1965), but the upper and middle KERZ are devoid of gravimetric stations, and the contours drawn across that area are merely inferred. The lower KERZ has been surveyed in some detail (Furumoto, 1976), and the resulting Bouguer anomaly map reveals a strong, elongate high, parallel to the rift, in the western part of the lower KERZ. The source of this feature has been modeled as a zone of high-density dikes and flanking sills, in which the top of the dike complex may rise to within 5,000 feet of the land surface (Broyles, 1977). The high-density rock is believed to be composed of olivine-rich gabbro with a density of 3.1 grams/cubic centimeter (g/cc), about 0.5 g/cc greater than the country rock. This density contrast is supported by high P-wave velocities (around 7.0 km/s) interpreted from seismic-refraction surveys.

In the vicinity of the Puulena Craters and geothermal well HGP-A, this gravity high appears to be offset slightly along a NNW-trending belt in a left-lateral sense. This subtle offset might not have been noticed and discussed were it not for the nearby presence of several wells that penetrate the high-temperature geothermal reservoir. This and other features of the gravity data are correlated with aeromagnetic anomalies. However, the gravity data of themselves do not provide clear or definitive geothermal targets.

3.1.2 Aeromagnetic Surveys

Aeromagnetic surveys were flown in 1966 and 1978 (Flanigan and others, 1986). The earlier survey was flown too high (13,000 feet above ground level, a.g.l.) to have resolution useful in characterizing shallow structures of geothermal interest, while the later one was flown at only 1,000 feet a.g.l., with flight lines separated by 2,600 to 5,200 feet. Because the regional (IGRF) field has a very small gradient (not more than 4 nT/km) in the area, it was not subtracted from the data by the authors in making the anomaly map. This survey shows steep linear gradients and associated dipolar anomalies aligned with most of the length of the KERZ, and positioned along its southern flank. The orientation of the dipoles is in accord with a remanent magnetization of the source bodies which is close to that of the present geomagnetic field, with an inclination of around 35° N. This implies that the source bodies had cooled to below the Curie temperature within the current polarity epoch (beginning 20,000 years ago).

Flanigan and others (1986) have modeled the typical anomaly pattern in terms of a 2-dimensional prismatic body which is about 8,200 feet wide and 6,600 feet high, with its top near the ground surface. This is considered to represent a complex of dikes that have higher magnetic susceptibility than the country rock. The model predicts that the anomaly extremes are approximately over the prism edges, so that the mapped extremes may be taken to locate the edges of the source. The magnetic susceptibility (K) contrast of the model is around 0.03 cgs units, with K higher in the source prism than in the country rock. This

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model agrees well with that put forward for the gravity anomaly in the lower KERZ.

In the Puna area, the aeromagnetic data appear more complex than to the west, and some researchers suggest that an offset of the anomaly pattern is present, similar to and perhaps related to the Bouguer gravity anomaly. However, neither the offset nor its relationship to the gravity data is obvious or compelling to the writers of the present report. Although the aeromagnetic data appear to be effective in illuminating intrusive structures of moderate to large dimension, it seems that they cannot resolve geothermal targets, such as that drilled successfully in the Puna area.

3.1.3 Passive Seismic Data

Since the 1950s, the Hawaiian Volcano Observatory (HVO) has operated a seismographic network, with stations located primarily in the vicinity of Kilauea and near the southern coast of the Island of Hawaii. The number and sensitivity of the seismographs have increased steadily since the network's inception: since 1969, virtually all shocks on the island with magnitude = 3 or larger have been located satisfactorily; by 1985, the magnitude threshold of complete detection and location had dropped to around 1. Tens of thousands of small shocks have been detected and located by the HVO during the past 30 years.

The positions, source mechanisms, and rates of occurrence of earthquakes, in relation to magmatic activity associated with Kilauea volcano and its rift zones, and with reference to the tectonics of the surrounding region, have been studied in great detail by a number of investigators. Scientific articles concerning these phenomena probably number several hundred, and this large body of work cannot be totally characterized here. However, a few important features are noted: since 1960, many tens of thousands of small earthquakes have been detected and located beneath Kilauea as well as beneath the KERZ and the Southwest Rift, at depths from nearly 0 to more than 35 miles; earthquakes associated with eruptive and intrusive magmatism occur in rather tight space-time clusters known as "swarms"; swarm shocks are small, with magnitudes that rarely exceed 4; shocks related to magmatism are caused by the fracturing that takes place when magma forces its way into and through brittle rock.

A recent review article (Klein and Koyanagi, 1989) presents an excellent, concise summary of the current understanding of seismicity in the southern part of the Island of Hawaii. This includes a presentation of the spatial distribution of earthquake foci in a number of maps and cross-sections, for the period 1970-84. The report and map by ENEL (1990) does not adequately present this kind of information. A cluster of shallow shocks (depths of 0 to 3 miles) is easily distinguished around the Puulena Craters and geothermal well HGP-A. Shallow and deeper (depths of 3 to 8 miles) clusters of shocks are centered north of Ka Lae Apuki, about 6,500 feet east of a resistivity low shown by the airborne EM/VLF survey discussed below. Other, less distinct, clusters seem to be present within the KERZ, but additional spatial analysis would be required to demonstrate or disprove their existence. The State of Hawaii has recently funded analysis of seismic data by HGEI, and the results of that work should include an appropriate graphical presentation of the information.

Microearthquake surveys have been carried out in the lower KERZ; one of the two surveys reported by Suyenaga and others (1978) indicated clustering of small shocks near well HGP-A, predominantly at depths of 3,000 to 15,000 feet. These workers conducted another survey, which indicated a cluster centered about 2-1/2 miles north of Kehena, near wells KS-1 and -2. This is the same area as a pronounced (SP) anomaly discussed below.

Based on the experience outlined above, passive seismic data are potentially useful in the delineation of geothermal targets in the KERZ. Further analysis of existing data is necessary.

3.1.4 Geoelectrical Surveys

Only one geoelectrical survey provides homogeneous coverage of the entire KERZ, and this is the EM/VLF mapping reported by Flanigan and others (1986). Ground-based geoelectrical soundings and surveys have been carried out in the lower KERZ and are of the following types:

- bipole-dipole, pole-dipole and TDEM or EM transient surveys (Skokan, 1974; Keller and others, 1977);
- vertical electrical soundings (VES or Schlumberger) and EM soundings (Kauahikaua and Klein, 1977; Kauahikaua and Mattice, 1981);
- a mise-al-a-masse survey (Kauahikaua and others, 1980); and
- an SP survey (Zablocki, 1977).

By far, most of the ground-based work has been conducted in the area extending easterly from the road between Pahoa and Kalapana to Kapoho Crater. A small number of bipole sources and VES spreads were located north of Pahoa to near Kurtistown, and three bipole sources were positioned near Kilauea Crater.

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The ENEL report (1990) makes a useful contribution in its compilation of a map showing transmitter sites for the various active geoelectrical surveys and soundings; however, receiver sites are shown only for the TDEM work, and not for the direct-current surveys. Also, the ENEL report includes a map compilation showing major results of the geoelectrical work, although it appears to oversimplify data which show great variability in electrical structure over distances of a few miles.

Most of the soundings (both direct-current and EM) have indicated a dry, highly resistive (hundreds to thousands of ohm-m) surficial layer above the water table, underlain by a saturated, more-conductive layer (1 to 600 ohm-m) with variable thickness; this is underlain by more-resistive ("electrical basement") material. The most significant variable is in the depth, thickness, and resistivity of this second, more-conductive layer. These factors appear to be controlled by the salinity and temperature of the ground-water, the possible existence of lenses of meteoric water over seawater (brine), and, to a lesser degree, by clay alteration. Except for the Puna area, the spatial density of sounding points has been insufficient to permit resistivity mapping with really useful resolution.

Because of their very uneven and frequently non-coincident spatial distribution, it is difficult to compare or synthesize results of the many ground-based geoelectrical surveys and soundings. Only the TDEM survey, with 24 soundings in the Puna district, has a sufficient spatial density of observation points to allow a useful mapping (that is, with horizontal resolution better than about 3 to 6 miles) of shallow, second-layer resistivity; this is shown in the ENEL report (1990). Of the 24 soundings, 17 were interpreted in terms of a layered model. The data indicate an ENE-trending low, some two miles wide, extending from the vicinity of well Ashida 1 to Kapoho Crater (ENEL,

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1990). This has resistivity of about 2 to 4 ohm-m for a second layer with a thickness of 1,500 to 3,500 feet.

The various surveys (bipole-dipole, pole-dipole, mise-a-la-masse) using fixed current sources and distributed receiver sites portray surficial resistivities at close range and second-layer resistivities at greater distance, making it quite difficult to combine the data. Only two bipoles were close enough to HGP-A to illuminate that area; they indicated apparent resistivities of around 10 ohm-m at HGP-A, and also that the well is positioned away from the lowest apparent resistivities (2 to 5 ohm-m). The depth of current penetration and true resistivities are unknown. The mise-a-la-masse survey, which used the casing of well HGP-A as one current electrode, showed a similar situation. The investigators speculated that these high apparent resistivities at HGP-A are the result of fresh water impounded upgradient of dikes.

The most interesting of the geoelectrical investigations is the SP survey carried out in the Puna district (Zablocki, 1977). The survey revealed four anomalies, of which at least two appear to be significant in relation to geothermal targets. One is a narrow, monopolar (positive) anomaly centered near well HGP-A, with an amplitude of 450 mV, and a long axis aligned with a 1790 eruption fissure. Another is bipolar, with peak-to-trough amplitude of nearly 800 mV, having its positive peak directly over steaming vents formed during the 1955 eruption; wells KS-1 and -2 are on this anomaly. The SP anomaly is modeled as being the result of an asymmetric convective plume, buttressed on its south side by an impervious dike.

A third SP anomaly is located about one-half mile to the northeast of HGP-A, and strikes northwest, cross-cutting fissures. It

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is noted that the ENEL (1990) report does not represent the SP data with sufficient accuracy. For example, the closed positive and negative anomalies are associated with KS-1 and -2, and should have been discussed.

Each of the reports listed above included speculations on the depth, temperature, and geothermal significance of circulating ground-waters. In our view, these remain simply speculations: they cannot be verified, and are sufficiently problematic to be not useful in resource estimates.

The EM/VLF survey had flight lines draped at about 350 feet a.g.l. and spaced at 3,000 to 6,500 feet, trending NNW, transverse to the trend of the KERZ. An apparent resistivity map was prepared for a transmitter frequency of 18.6 kHz, with attendant skin depth of 100 to 1,300 feet, depending on actual shallow resistivity. This map reveals three major lows which appear as troughs, about one to three miles in width, that cross-cut the KERZ.

The most easterly of these runs northerly from Opihikao through the Puna area to a point about 3 miles north of HGP-A, and has apparent resistivities of 25 to 600 ohm-m. It is thought that this trough reflects shallow circulation of ground-water, and perhaps clay alteration, enhanced by faults and fractures which cross-cut the KERZ, and along which several productive geothermal wells are found.

The middle and western troughs run northerly from Kupapau Point and Ka Lai Apuki, respectively, and no other geophysical or structural geologic features appear to be correlated with their positions.

Reiterating, it appears that the SP method, and perhaps resistivity soundings, may be useful in selection of geothermal targets in Hawaii. Data distribution is insufficient to allow more definite conclusions. Only further drilling and testing of deep wells can confirm or refute these tentative findings.

3.1.5 Ranking and Recommendations for Obtaining Additional Geophysical Data

A priority ranking is presented, which considers three factors: the logistical problems (physical access to survey areas), expense, and ability to resolve a geothermal target. The geophysical methods are listed in order of decreasing priority, and explanations are given below:

1. SP surveys over selected areas
2. Detailed spatial analysis of existing HVO seismicity data
3. Airborne EM/VLF surveys in selected areas
4. Resistivity soundings (VES/Schlumberger or TDEM)
5. Gravimetry, resistivity surveys, and aeromagnetics

Self-Potential Surveys

SP surveys in selected areas, not larger than approximately 20 square miles, may be able to define anomalies containing geothermal resources, should they exist, with a precision better than one-half mile. SP surveys identify geothermal targets, through the detection of electrical streaming potentials often associated with shallow hydrothermal plumes.

Among the geoelectrical methods, SP surveys are probably the easiest to conduct on foot, as one man can carry the required receiver, porous pots, and a small reel of wire for short spread-lengths. Portable global-positioning receivers are now available, making it easy to establish precise coordinates for remote observing stations. Off-road portability of equipment and locatability are critical considerations for ground-based exploration in the KERZ, as much of the area has no road access, and land surveying is inconvenient in the dense tropical forest.

Selection of field areas in which to conduct SP surveys can be based on available data from several other exploration activities, including passive seismic (HVO data), EM/VLF mapping, surficial geologic structure, locations of historically formed fissures and steam vents and, especially, results from recently drilled wells. However, before additional SP work is proposed, the initial SP survey field data should be replicated first to see whether this method provides consistent and applicable results. There may be changes in the local SP field since the Zablocki (1977) survey.

HVO Seismicity Data (Passive Seismic)

Detailed spatial analysis of the enormously large set of earthquake locations available for the KERZ and KSWRZ offers a relatively inexpensive means of identifying shallow (0 to 3 miles deep) seismicity that may be linked to significant, on-going hydrothermal activity in the upper crust. No field work is required to conduct this study. Analysis would rely primarily on preparation of maps and cross-sections of earthquake hypocenters within selected rectangular crustal blocks; it would be useful to apply moving time-of-occurrence windows to identify swarms, which appear to be more related to geothermal activity

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than non-swarm events. Location of targets may have a precision of about 3,000 feet.

Detonation of a few "calibration shots" in the KERZ (and perhaps also in the KSWRZ) could be used to significantly improve the accuracy of hypocentral locations (by appropriate reprocessing of hypocenters already located). Some of the analyses and calibration shooting may already have been done by the HVO, and maps and cross-sections may be available to inspection by interested scientists.

Short-term microearthquake surveys, using state-of-the-art equipment (PASSCAL portable seismographs) may be appropriate after there has been a thorough analysis and interpretation of the large mass of available data. In this way, structural and earthquake-source features developed from HVO data may be methodically investigated.

Airborne EM/VLF Surveys

The existing airborne EM/VLF mapping reveals three interesting low-resistivity troughs that cross-cut the KERZ. The easternmost of these transects the Puna area, and includes the geothermal resource already drilled (HGP-A) in the vicinity of the Puulena Craters. It is obvious that parts of the troughs also extend outside of the areas of the geothermal reservoir, but geology enables us to exclude these parts of the troughs from consideration for geothermal exploration. The possible geological, hydrological and thermal features related to the troughs remain to be analyzed.

It might be worthwhile to conduct additional EM/VLF surveys, with higher resolution (using closer-spaced flight lines) and incorporating lower frequencies (to provide deeper penetration) than the

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existing survey, but only in selected areas. Selection of areas for future exploration may be guided by (a) the locations of the two resistivity troughs lying west of the Puna area, (b) locations of seismicity clusters, and, of course, (c) surficial geologic features.

Resistivity Soundings

Resistivity soundings are rather cumbersome to make, and are not practical without road access. It may ultimately be worthwhile to fill in some gaps left by previous sounding efforts (TDEM and VES) in the Puna area, where there is relatively good road access. Such work might help to better define the extent of the Puna geothermal reservoir. Before this is done, additional review of exiting exploration data would be required, in order to specify worthwhile locations.

Resistivity Surveys, Gravimetry, Aeromagnetics

Based on experience to date, each method has had some utility in defining regional, and occasionally local, geologic structure. In this regard the gravimetric survey has led to the identification and quantification of the dike swarm intruded into the KERZ which is believed by many workers to form the principal heat source of the geothermal system. Repeat gravimetry may in the future allow the recognition of additional dike emplacements at depth beneath the KERZ through changes in mass (density) distributions at previously measured stations.

Having said that, however, none of these methods is considered capable of providing sufficient resolution of geologic structure in all-volcanic terrain, or in detection of hydrothermal plumes, to be clearly useful in the detailed stage of geothermal exploration involving siting wells or calculating reserves of geothermal energy. Gravity data in the Puna area are confined to a few roads; the available Bouguer gravity map (Furumoto and others, 1976) interpolates these data. Several gravity stations were located along an approximate east-west traverse through the geothermal district. It may be useful to make more observations (fill gaps) along this traverse and to model all data, old and new. Otherwise no further work is recommended at this time.

3.2 Geochemical Surveys

3.2.1 Ground-Water Surveys

Several compilations and reviews of ground-water chemistry in the KERZ and its surroundings have been published (Cox, 1980; Cox, 1981; ENEL, 1990; Iovenitti, 1990; Thomas, 1986; Thomas, 1987; Thomas, 1989). These, along with discussions with scientists and private operators recently active in the area, form the basis for the following observations and conclusions. A partial tabulation of the geochemistry database appears as tables 3.1 and 3.2; an assessment of the chemistry of the deep thermal system is described in Chapter 5.2; a discussion of chemical impacts and risks is given in Chapter 7.2. Table 3.1 lists groundwater samples and includes all available data for Mg, Cl and sample temperature (listed as TF), but more complete data for selected samples only. Table 3.2 shows deep well data.

As ENEL (1990) has pointed out, much of the available chemical data base is fragmentary, incomplete, and often marginal in quality. Sample locations often are ambiguous, and analyses of samples from single locations collected years apart sometimes differ. Most analyses lack trace elements, such as B, Li, Rb, Br and Cs, and the stable isotopes of oxygen and hydrogen. One-half of 94 major element analyses reported by ENEL (1990) show major element ion imbalances of more than 10%.

The analyses compiled by ENEL probably did not include all information possible from the U.S. Geological Survey or the State of Hawaii, and we are not sure that the other reports cited in Chapter 10 combine with the ENEL report to make a comprehensive list. Overall, the disorganization of the chemical data base is surprising, considering the importance attached to it by all parties.

Geochemical surveys of ground-waters in the area also are limited by the relatively small number of boreholes, wells and springs. Figures 3.2 and 3.3 show all sources of chemical data listed in the referenced sources, providing for each one a name and U.S.Geological Survey number. However, because the data sources are ambiguous, some locations are uncertain (for example, Pahoa, Hawn Shores, Allison, Malama Ki), some U.S. Geological Survey numbers are uncertain, and even some names are uncertain. The locations of the KS-series wells and MW-series monitor holes on figures 3.2 and 3.3 are based on survey data, and should be accurate.

Although it is therefore possible that some analyses have been misclassified, and although some of the chemical data are not of the best quality, the general survey results described below suggest that major chemical surprises are unlikely in future geochemical results.

The ground-water sample locations with the exception of Isaac Hale Spring, are mostly shallow wells which penetrate to no more than about 100 feet below sea level. Hole GTW-4 is an exception which terminates above sea level and apparently taps perched water. Information about the Kapoho Test and Kopoho Crater holes is ambiguous:

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these may or may not reach sea level. The depths of the PGV monitor wells (MW-1, -2 and -3) have not been reported, but they probably penetrate at least to sea level.

Ground-water compositions in the Puna area are determined by various factors:

(a) low-temperature reactions between meteoric water and volcanic rock minerals;

(b) the marine origin of the meteoric component (presence of sea salts);

(c) mixing of meteoric water and seawater in the subsurface;

(d) hydrothermal alteration of meteoric water;

(e) hydrothermal alteration of seawater; and

(f) mixing of the various components.

The coolest, most-dilute waters in the area, with less than about 100 mg/l of chloride ion (Cl), also have low levels of alkalinity and sulfates, and mixed cation concentrations which reflect the mineral composition of the volcanic rocks. Mixing with cool seawater raises the Cl concentration, and adds considerable amounts of other cations and anions as well.

Hydrothermal alteration of meteoric water in basalts tends to produce Cl concentrations of a few thousand to several thousand mg/l, the exact amount being determined by the amount of Cl originally present in the rock. In contrast, hydrothermally altered seawater tends to have Cl close to the 19,000 mg/l present in seawater. Whether originating as meteoric water or as seawater, however, hydrothermal water tends to develop certain other characteristics as a result of temperature-dependent rock-water reactions: high silica (SiO_2), decreasing sodium/potassium (Na/K), very low magnesium (Mg), low bicarbonate (HCO_3), and low sulfate (SO_4). In sum, hydrothermal water usually has a composition dominated by sodium and chloride, with SiO_2 increasing and Mg and Na/K decreasing as temperature rises. If the hydrothermal water originated as meteoric water, Ca tends to be less than about 100 mg/l. In contrast, if the hydrothermal water originated as seawater (400 mg/l Ca), the hot water may contain 500 to 1,500 mg/l of this element.

In a review of about 400 ground-water samples from the State of Hawaii, Cox and Thomas (1979) decided that three parameters could be considered diagnostic of water considered "geothermal": temperature > 84°F; Cl/Mg ratio equal to or greater than 15; and SiO_2 concentration >30 to 85, depending upon location. ENEL (1990) also used the Cl/Mg ratio as a diagnostic tool, because the ratio Cl/Mg=15 is that of seawater, and a higher ratio will result from heating.

Six of the shallow sample locations meet the criterion of temperature >84°F. Among these, Isaac Hale Spring is the only coastal warm spring from which an analysis has been reported. ENEL (1990) showed the temperature and approximate location of some 10 springs and shallow wells along the coast south of the rift, and one to the north. However, temperatures exceed 86°F only at Isaac Hale, Allison, and Opihikau springs. D. Thomas (oral communication, 1991) reported that Isaac Hale and Opihikau are the only locations where hot water discharge can be sampled before it mixes with seawater.

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Figure 3.4 shows the Cl/Mg ratio of the shallow ground-waters, and of the waters from deep geothermal wells in the area. The ratio is illustrated by plotting both Cl and Mg on log axes, which places waters of equal Cl/Mg on diagonal distributions.

The groundwaters with Cl<100 mg/l and Cl/Mg<15 (Hawn Shores, Pahoa, Kapoho Crater, MW-1 all have temperatures < 84°F and compositions determined by low-temperature interaction of marine meteoric water and volcanic rocks.

Ground waters with Cl>100 mg/l and Cl/Mg≈15 are mixtures of meteoric water and seawater. These include Isaac Hale Spring (97°F) and Malama-Ki (126 to 131°F), in which other ion ratios also indicate the presence of cool or minimally altered seawater mixed with meteoric water. Allison well (100°F) may also be included. ENEL (1990) estimated the seawater component in Malama-Ki as 21 to 27%. None of these waters appears to have SiO_2>80 mg/l, with the exception of one sample from Malama-Ki that shows 100 mg/l.

The Isaac Hale and Malama-Ki waters have been heated, of course, but it is not possible to tell when heating occurred relative to the mixing event, except that substantial heating of the seawater component is disallowed by the relatively low Cl/Mg value. Iovenitti (1990) has interpreted these same waters as mixtures of dilute ground-water with thermal reservoir outflow (meaning outflow from the deep system beneath the KERZ), but the data do not clearly establish this. Limited mixing with thermal reservoir outflow also has been hypothesized by Thomas (1987).

The ground-waters shown on figure 3.4 with Cl>100 mg/l and Cl/Mg>30 more strongly indicate a thermal effect. These waters include samples from MW-2 (no temperature available), GTW-3 (165 to 203°F), and single samples each from tests KS-1 (113°F), KS-1A (>100°F), and KS-2 (<100°F), all described by Iovenitti (1990) as "top of dike-impounded water". The geothermal signature of these ground-waters is indicated also by SiO_2 concentrations in the range 80 to 180 mg/l, except at MW-2 (~45 mg/l). The signature is not surprising, given that the sites are all within the KERZ. A single dilute sample from the Ashida 1 well more-or-less falls into this group, but its origin and temperature are uncertain, and SiO_2 content unknown. Keauohana may be considered ambiguous: it has Cl reported in the range 70-160 mg/l, and Cl/Mg slightly above 15, but reported temperatures of 70-84°F and SiO_2 below 50 mg/l. The deeper thermal waters on figure 3.1.2c, all with Cl/Mg>1,000, are described in Chapter 5.2.

These results may be summarized by pointing out (a) the small number of sample locations, and (b) the limited evidence of outflow from the thermal system which lies below the KERZ. To the north of the KERZ there is no evidence of thermal water. Shallow, moderately hot waters occur within the KERZ, as at hole GTW-3. To the south, where hot water is found at Malama-Ki, the Allison well, Issac Hale Spring, and other springs scattered along the coast, none produces water with a strong and unambiguous geothermal chemistry signature. This is either because mixing with cool seawater has masked a geothermal component, or because heating has been local and limited in its effect on chemistry. In any case, the area south of the KERZ lacks clear evidence of a massive, very high-temperature outflow from the rift zone.

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3.2.2 Trace-Emissions Surveys

Because the KERZ lacks a shallow water table and such surface expressions of hydrothermal activity as hot springs and fumaroles, exploration to detect trace-level emissions of volatile species has been done in the form of soil surveys for Hg and ^{222}Rn. Cox (1980, 1981) conducted reconnaissance-level sampling at spacings of about 1,500 to 2,500 feet (Hg) and 3,000 to 5,000 feet (^{222}Rn), in the lower KERZ.

Reducing the Hg data to remove strong background effects of soil chemistry was particularly difficult; the reduced data presented "a pattern of anomalous Hg overall (which) indicates Hg leakage in ground gas from fractures within the rift zone and tends to reinforce the model of a rift-controlled reservoir" (Cox, 1981; p.70). There were localized variations, some of which may be related to the influence of specific fractures, but most of which appeared to be a function of problems with data reduction. The major Hg anomaly included the location of well HGP-A.

The ^{222}Rn survey was regarded by Cox (1980) as somewhat more successful in defining zones of possible deep permeability and thermal activity. There are several anomalies, all within the KERZ, encompassing the locations of HGP-A and the PGV wells. The anomalies were interpreted to be zones of high temperature and structural permeability, allowing ground-gas movement (outgassing of deep vapor bearing ^{222}Rn) which is detectable near the surface (Cox, 1980). However, D. Thomas (oral communication, 1991) suspects that the anomalies are created by variations in local, shallow subsurface permeability, and do not necessarily indicate good exploration targets.

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The ^{222}Rn and Hg surveys both allow correlations between gas anomalies and the KERZ, and show an anomaly at the proven HGP-A and PGV wellfield. However, the HGP-A discovery was made without the benefit of these data, and the PGV discovery wells probably also were sited using other criteria. The unproductive, deep Lanipuna wells just south and southeast of the wellfield are at the edge or outside of the anomalies. This may encourage the siting of future exploration wells within the ^{222}Rn anomalies, the Hg data being too uncertain for such use. However, the actual <u>utility</u> of the soil chemistry data as a tool for siting wells and proving deep, productive reservoir(s) remains to be established. Data from drilling into the other ^{222}Rn anomalies are needed.

4. RESULTS AND STATUS OF DRILLING AND FIELD DEVELOPMENT

4.1 History and Status of Drilling in the KERZ

Some fourteen deep holes have been drilled into the KERZ since 1976, including sub-areas Puna geothermal reservoir and Kilauea Middle East Rift Zone (KMERZ), by a total of five different operators (table 4.1). Nine of these wells have proved the Puna geothermal reservoir (figure 3.1 and 3.2). Appendix A presents summary plots of the available downhole data for these wells.

Hot water and steam at temperatures of up to 680°F exist in a reservoir lying generally between the depths of 4,000 to 7,000 feet. Wells KS-7 and KS-8, drilled by PGV in 1991, may have found geothermal resources at shallower depths (1,800 feet and 3,400 feet, respectively), but reliable data are not yet available. The Puna reservoir is one of the hottest in the United States; in fact, only three other producing geothermal fields in the United States (The Geysers, Salton Sea and Coso Hot Springs, all in California) have displayed such high fluid temperatures. (All three of these fields produce geothermal electricity commercially.)

The Puna discovery well, HGP-A, was drilled for the State of Hawaii in 1976; it supplied fluid to a 3-MW demonstration power plant from 1982 to 1989. Three wells (Ashida 1, Lanipuna 1 and Lanipuna 6) were drilled by Barnwell Industries between 1981 and 1984. These wells proved to be unproductive, as was a sidetrack of Lanipuna 1. However, the wells provided valuable subsurface temperature and geologic information. Temperatures in excess of 685°F were measured at the bottom of Lanipuna 1; a temperature of 550°F was measured at the bottom

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of Ashida 1; neither well could sustain flow. Lanipuna 6 was comparatively cold (335°F), but may be usable as an injection well.

Three wells were drilled and flow tested by Thermal Power Company on its Kapoho State (KS) lease between 1981 and 1985. KS-1 and -2 currently are not usable, because of mechanical well damage; however, these two wells originally were capable of producing about 3 MW and 2 MW, respectively. KS-1A also had an initial capacity equal to about 3 MW, and it also was damaged and can no longer be produced. However, it still may be useful as an injection well.

Three cored holes (SOH-1, -2 and -4) were drilled as part of the State's Scientific Observation Hole (SOH) program in 1990-91. The purpose of these wells is to delineate zones of anomolously high subsurface temperatures, and to characterize the lithologic and hydraulic properties of the zones they penetrate.

Despite its number, well SOH-4 was the first of the program. Located about 2-1/2 miles from the True-Mid Pacific KMERZ drilling site, the well was completed on 20 May 1990 to a depth of 6,562 feet. Partial and total losses of circulation were observed during drilling.

Well SOH-1 was drilled second. Located approximately 2,000 feet north of the PGV power plant site, the well was completed on 6 January 1991 to a total depth of 5,526 feet. During drilling, partial losses of circulation were encountered, mainly below 3,900 feet. The maximum measured temperature of 408°F in well SOH-1 indicates that the reservoir being investigated by PGV probably does not extend as far as the site of well SOH-1.

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Well SOH-2 was completed on 4 June 1991 to a depth of 6,802 feet. The well is located in the lower KERZ, approximately three miles northeast of well SOH-1. The maximum measured temperature, two days after the well had been drilled and prior to the injection test, was 661°F. Both partial and total losses of circulation were recorded while drilling.

During 1990-91, PGV drilled three geothermal tests, KS-3, -7 and -8. Most data from these wells are not yet public. All three wells intercepted potentially productive targets in the geothermal reservoir. Well KS-3 is completed as a production well, but may be converted into an injection well. Well KS-7 was drilled as an injection well, but intercepted high-pressure steam and gas at less than 2,000 feet in depth, and has been plugged back. The casing program of KS-7 was insufficient to allow conversion for production (see Chapter 7.1). Well KS-8 also encountered high-pressure steam and gas at about 3,400 feet in depth. A blowout and uncontrolled release of H_2S caused the County to suspend its permit in June 1991. Consequently, PGV's activities are at a near-standstill.

PGV has just been notified that is permit is being reinstated, with additional requirements and conditions. PGV apparently will complete and test well KS-8 for production, workover and test wells KS-1A and -3 for injection, and then drill such additional production and injection wells as are needed to operate its power plant.

PGV originally estimated that as many as eight production wells, with productivity of about 3 to 3.5 MW each, would be required in order to supply steam to a 25 MW (net) power plant. It is speculated that wells such as KS-8 may produce as much as 10 MW each, reducing the number of wells needed to supply the plant.

The injection requirement for the 25 MW (net) development is estimated to be approximately 1,400 gallons per minute (gpm). It is possible that two injection wells will be sufficient to dispose of all wastewater and non-condensible gases from the power plant. PGV intends to drill two injection wells and keep one on standby.

Between 1989 and 1991, True-Mid Pacific Geothermal drilled a well with one sidetrack and three redrills on its leasehold, located about eight miles WSW of the PGV drilling area. Several of the legs appear to have intercepted hot, permeable zones; data in the public domain are incomplete.

Well KMERZ A-1, was spudded on 12 November 1989; drilling of the original hole and A-1 Sidetrack, A-1 Redrill 2, A-1 Redrill 3 and A-1 Redrill 4 proceeded with various interruptions until November 1990. Testing continued until at least April 1991.

The holes were drilled with considerable difficulty, marked by episodes of stuck drill pipe, premature hanger setting, stuck casing, shallow zones of lost circulation, and drill pipe twistoffs. The initial hole was eventually drilled to a total depth of 8,651 feet on 4 March 1990. Lost circulation was reported at depths less than 6,000 feet, but there is no record of the surface production of steam. KMERZ A-1 Sidetrack 1 was drilled between January 1990 and March 1990 from a window milled in the 13-3/8" casing of KMERZ A-1 at 3,495 feet. It reached a depth of 8,741 feet, which appears to have been the deepest penetration by any of the legs of KMERZ A-1. Some steam entries were reported between about 7,100 and 8,100 feet. The hole was directed southward and horizontal departure was 2,044 feet at total depth.

Hole A-1 Redrill 2 was drilled to a depth of 7,824 feet in March and April 1990, eastward, with horizontal departure of 2,776 feet at total depth. Numerous steam entries were reported between about 6,000 and 7,600 feet.

Hole A-1 Redrill 3 was drilled in August and September 1990, from 2,734 to 7,658 feet in depth, also from a window cut in the 13-3/8" casing. Its direction was northeastward; horizontal departure was 2,269 feet at total depth. Steam entries were reported at a few intervals at about 7,550 feet. There was considerable bridging within the hole.

Hole A-1 Redrill 4 was drilled in October and November 1990. It was kicked off from Redrill 3 at a depth of 5,400 feet, and reached a total depth of 7,850 feet. Its direction was northeastward, twinning Redrill 3, with horizontal departure of 2,434 feet at total depth. Problems were encountered with sticking the drill pipe. Steam entries were reported near hole bottom.

The history of the True drilling operation appears to have been poorly documented by the drilling team in daily reports and test results submitted to the State. The record of major events appears to be incomplete.

4.2 Summary of Well-Test Results

Several well tests have been reported from the Puna geothermal wells. The earliest data come from HGP-A, completed in 1976. This well produced steam for a 3 MW demonstration plant at 82% capacity plant

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factor from 1982 to 1989. HGP-A was tested in 1976, using the James method with weir measurements. A total flow rate between 114,000 to 120,000 pounds per hour (114 to 120 KPH) was measured at a wellhead pressure of 59 pounds per square inch (psig).

During the testing of KS-1 and -2, it was observed that although the wells initially produced hot water, they would quickly change to production of steam. Further testing, conducted using a flash separator, confirmed this condition.

A total of five short-term rig-tests were conducted on KS-1, between 14 October and 10 November 1981. A short-term test was attempted in December 1981, during which it became apparent that the well had suffered damage. After a workover of the well, a further series of tests was conducted in August 1982. During these tests, the measured production rate varied around 70 kph at 120 psig wellhead pressure, and the maximum temperature (650°F) was measured at 6,400 feet. Under shut-in conditions, the wellhead pressure would increase rapidly, until it reached an equilibrium point at which the water level in the well was depressed to the level of the 9-5/8-inch casing shoe. A temperature and pressure survey run in February 1983 showed that the well had developed another casing leak at 670 feet.

A rig test and several short-term tests were conducted in KS-2 between March and June 1982. A maximum temperature of 670°F was measured at 6,900 feet. During the month of June 1982, a longer test was conducted, followed by a pressure-buildup test. During this test, the flow rate stabilized at about 150 KPH at 150 psig wellhead pressure, a significantly higher rate than had been measured in KS-1. In July 1982, a temperature survey indicated a casing leak at an approximate depth of 1,000 feet. Another flow test was conducted, despite the casing leak, during the months of July and August 1982. During this testing period, the behavior of the well clearly showed it was being affected by the leak.

Well KS-1A was tested with a flash separator during October 1985. Temperature measurements, performed during and after the test, indicated a maximum temperature of 670°F at 6,500 feet (bottomhole). Unlike wells KS-1 and -2, well KS-1A produced a mixture of about 75% steam and 25% water. Analysis of the flow data indicated that the well can produce up to 3.1 MW. A spinner survey run during the test indicated that the well produces about 50% of its total volumetric flow from between 4,500 and 5,500 feet, while the rest is produced from zones below 6,300 feet. An injection-falloff test and a buildup survey were conducted at the end of the test. The buildup data were affected by internal flow within the well.

The SOH wells were not permitted for flow tests, and consequently were tested for permeability by injection. Temperature surveys were conducted during injection and under static conditions.

In hole SOH-4, a maximum temperature of 576°F was recorded at a point below 6,400 in feet depth. Low permeability was indicated by a conductive temperature profile. In well SOH-2, the maximum recorded temperature is 661°F at 6,782 feet. Overall, the permeability is low; however, a permeable zone was observed between 4,200 and 4,900. The temperatures in this zone range from 280°F to 420°F. The maximum temperature in hole SOH-1 was 408°F, measured at a depth of 5,500 feet. A permeable fracture was observed at depths between 4,180 and 4,220 feet, at temperatures of less than 200°F.

Test results are very limited for the PGV well KS-3, and KS-7 and -8 have not been tested or evaluated completely, because of the high-pressure gas and steam discharges from both. After permits are restored to PGV, to allow well workover and testing to be completed, better assessments will be possible. However, the results from KS-3 are very similar to those reported for KS-1A and it is estimated that the well was capable of producing 3.2 MW after completion. Subsequent damage to the liner (possibly caused by corrosion) reduced the capacity of the well considerably and PGV is considered using KS-3 as well as KS-1A for injection.

The True KMERZ A-1 well has been tested, but only fragmentary test data are available. The following observations were provided: Steam entries mainly occurred at elevations between -6,000 and -7,000 feet (relative to mean sea level, msl). Fluids reaching the surface were "90% steam". Redrill 2 apparently was tested through a 6-inch orifice; the only reported results of the test were "17.2 psi and 247°F?" (Drilling Superintendents's log). When redrill 3 was tested, "lots of rocks and dirt" were produced, and then the well died. The flow temperature was reported to be 213°F.

After a 7-inch liner was installed in Redrill 4, it was flowed through an orifice plate at 10 to 15 kph, at temperatures as high as 261°F. Lost circulation, but no steam entries, had been reported by the mud loggers.

The tested output of A-1 and its Sidetrack and Redrills may be able to support up to 3 MW of power production, based on this fragmentary data. However, this number must be used with caution, pending more comprehensive test results.

Detailed analyses of well-test data are presented in Chapter 6.1 of this report, and downhole summary plots, which include all available completion information and temperature data, are presented in Appendix A.

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5. CONCEPTUAL MODEL OF THE GEOTHERMAL RESOURCE

5.1 Geologic Framework

The Puna geothermal field is located within the KERZ on the eastern side of Kilauea volcano (figures 3.1, 3.2 and 5.1). The KERZ extends from Kilauea's central caldera in a 25-mile linear course to the northeast coast of the Island of Hawaii, with a further 43-mile submarine extension. In the vicinity of the HGP-A and PGV developments, the rift is about 1.5 miles wide, as indicated by both surface morphology and aeromagnetic anomalies.

At the surface, the KERZ is marked by open fissures and lines of cinder and spatter cones. From knowledge of older rifts in the Hawaiian Islands, now exposed by erosion, rift zones in the subsurface consist of sets of fractures filled by swarms of closely spaced, nearly vertical, and nearly parallel dikes. In the central part of a main fissure zone, the number of dikes typically ranges between 100 and 200 per mile of zone width, with a maximum of about 1,000 per mile. Individual dikes average approximately three to five feet wide. Along the length of the KERZ, including the Puna area, the most recently active fissures are located on the southern boundary of the dike complex.

Structural and stratigraphic information for the Puna field comes from the following sources:

a) surface geologic mapping and interpretation of aerial photographs;

b) geophysical surveys, principally gravimetry and passive seismic surveys, but also aeromagnetic and geoelectrical surveys; and

c) lithologic and other logs available from exploration drilling.

5.1.1 Surface Geologic Features

The most important geologic feature within the KERZ relevant to the geothermal resource is the set of fissures through which lava was erupted in 1955. The fissures correspond to the most recently heated area of shallow rock, and clearly are relevant to the probable distribution of temperatures along the rift. The surface traces of these fissures are marked by linear trends of small craters and by small scarps representing recent fault offsets. The fissures and scarps strike N60°E in an *en echelon* pattern. The locations of a few of these features, as mapped from large-scale aerial photographs, are shown in figures 3.1, 3.2 and 5.1.

Wells KS-1 and -2 are drilled very close to the fissure zone, which continues in an *en echelon* pattern for 3.5 miles to the northeast. The fissure zone terminates at the small unnamed crater from which the extensive lava flow of 1960 was erupted. This vent is located 0.8 miles northwest of Kapoho crater.

Just to the southwest of wells KS-1 and HGP-A, the fissure zone is offset 0.8 miles to the SE. It has been postulated by a number of geologists and geophysicists that this offset is an important transverse fault, to which the Puna field is in some way genetically related. However, there are no NW-trending fractures on the surface to indicate the presence of this postulated transverse fault; and, as was discussed in Chapter 3, the main geophysical and geochemical evidence of its existence are the discontinuities observed in the patterns of the magnetic and mercury-gas anomalies.

The main eruptive fissure extends another 6 miles to the southwest, beyond the NW-trending offset zone; however, no recent eruptions have occurred along the 2-mile length nearest the offset. The Puulena Craters (figure 5.1), which parallels the fissure just to the southwest of the offset, are an old feature, with no record of historic eruptions.

5.1.2 Subsurface Geology

The lithologic logs of all but two of the exploration wells drilled in the KERZ record a sequence of basalts from the ground surface to their total depth. The principal variations consist of the irregular occurrence of alteration zones, and a gradual decrease in the ratio of vesicular to non-vesicular lava with depth. A change from sub-aerial to shoreline-deposited flows occurs at about 3,000 feet in depth, followed by 1,000 feet of "transition zone" hyaloclastite flows, submarine flows to about 6,500 feet in depth, and intrusive dikes below 6,500 feet.

The top several hundred feet of the hyaloclastites has been proposed by some investigators to be a cap rock above the geothermal reservoir. However, well KS-8 apparently encountered geothermal steam and hot water before penetrating this zone.

Well KMERZ A-1, in addition to penetrating basalts of the Kilaula volcano sequence, penetrated limestone (presumably coralline) in two of its legs at about 5,000 to 6,000 feet in depth. It is also probable that the well penetrated pre-Kilauea (Mauna Loa sequence) volcanic rocks. Well SOH-4 also penetrated shallow marine carbonates (corraline limestone?) from about 5,300 to 6,100 feet in depth, and may possibly have penetrated Mauna Loa shield volcanic rocks.

Other important geological parameters contained on the lithologic logs are the locations of zones of lost circulation. This information is included on the summary plots for each well (Appendix A).

5.2 Reservoir Fluid Chemistry

Water-sample data from wells HGP-A, KS-1A, KS-2, Lanipuna 1 and Lanipuna 6 are listed in table 3.2, along with data from a single sample recently reported from well KS-3. Analyses of other fluids from the newer deep wells are not yet available. Background information pertaining to data in table 3.2 is as follows:

> There are numerous published analyses of waters from well HGP-A (for example, ENEL, 1990). These data include many weir samples, and liquid, steam and gas samples collected at production-line pressure, but do not include stable-isotope analyses. The well was not precisely flow-metered, so that the total-flow enthalpy and steam fractions are not well-known. Major ion balances of the published analyses are quite satisfactory. For this report, HGP-A is represented by selected samples which illustrate the well's chemistry since it was first tested in 1976, through the beginning of regular production in 1981, until 1984. More recent data have been published only in graphical and narrative formats (Thomas, 1987b). Analyses of the non-condensible gases also are available.

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KS-1A was sampled during a flow test in October 1985. All known analyses are listed. Gas data also are available.

KS-1 was sampled during testing in April and June 1982, but tabulations of the analyses are not available except for some measurements of Cl. Limited gas data are available.

KS-2 testing produced steam with very little water. There is one partial analysis of the liquid phase, along with analyses of the steam and gases, but the results are incomplete and were plagued by technical problems (J. Iovenitti, memorandum dated 16 October 1987).

KS-3 is represented by a single sample from a flow test in about April 1991, recently released by PGV. Background information is not available. The sample is highly concentrated, and may have undergone excess evaporation as the result of there being an extremely high steam fraction in the total flow.

Lanipuna 1 and Lanipuna 6 were sampled during brief pumping by air lift. All analyses are listed.

5.2.1 Excess-Steam Effects

Table 3.2 lists all samples as collected. Samples from wells HGP-A, KS-1A, KS-2 and KS-3 were affected by boiling and separation of steam prior to sample collection. Therefore, to compare reservoir conditions at these wells, it is necessary to correct the sample analyses to reservoir liquid concentrations, by removing the boiling and steam-separation effects. This is easily done, using the steam fraction at separation pressure, at which point a well produces only water into the wellbore and boiling does not begin until the fluid begins ascending the well.

However, these wells produce a high steam fraction, which includes "excess" steam produced directly from the reservoir. At HGP-A there was about 43 wt% steam at a production separator pressure of 170 psia; and at KS-1A there was about 83 wt% steam at 170 psia. At least some of the excess steam probably forms in response to pressure drawdown and boiling in the reservoir when the well is produced. Because of the excess steam, the concentrations of dissolved solids and gases in the total flow of the well are not the same as in the reservoir prior to well production. To describe reservoir conditions, it is necessary to know what fraction of total steam present at sampling conditions represents the "excess" steam, and what fraction represents boiling of reservoir liquid which entered the well.

These fractions can be estimated using either (a) measured production-zone temperature(s) or (b) chemical geothermometers, to calculate the reservoir-liquid temperature and enthalpy prior to production, and to compare these with the enthalpy of total flow at the wellhead. The reservoir enthalpy value is used to calculate the steam fraction at sample-separation pressure; and that value, instead of the measured total steam fraction, is used to correct the sample analyses to the pre-flash reservoir-liquid concentrations.

Reasonable results often can be obtained using the quartz, adiabatic geothermometer. However, there are numerous uncertainties introduced by analytical errors, sampling errors, mixing of fluids from different production zones, and loss of SiO_2 during scale formation before sampling. The uncertainty is largest for well KS-1A, where the very high steam fraction could have caused excessive evaporation of the liquid phase. However, the results still allow gross comparisons between wells, and within individual wells over time. (The sample from KS-3 appears to have undergone excessive evaporation, because of extreme excess steam, and will not be considered.)

Table 5.1 shows the analyses from wells HGP-A and KS-1A corrected to average reservoir-liquid composition, using enthalpy and steam fraction determined from the quartz, adiabatic geothermometer. The method requires an analysis of SiO_2 and documentation of separation pressure; samples lacking this information, including the one sample from well KS-2, are omitted. Also omitted are four samples (numbers 20, 21, 24 and 28) from well KS-1A which contained higher levels of SiO_2 than can possibly have been reached at the recorded separation pressure, unless there was extreme excess evaporation caused by a very high steam fraction, which invalidates the geothermometer.

As discussed below, the quartz temperatures obtained from well KS-1A average about 50°F lower (575°F) than the probable main reservoir temperature (625°F). If the reservoir-liquid enthalpy (based on quartz temperatures) has been underestimated, then the steam fraction to correct surface samples to reservoir conditions also has been underestimated. The quartz temperatures yielded steam fractions at sampling pressure of 25 to 30 wt%. In contrast, a reservoir-liquid temperature, before boiling, of 625°F yields steam fractions of about 35 wt%, which lowers the reservoir concentrations by about 10% to 15% below the values in table 5.1.

5.2.2 Reservoir-Liquid Compositions

Dissolved solids in the Puna reservoir liquids are dominantly Na and Cl. The overall composition commonly is characteristic of seawater hydrothermally altered during reactions with basaltic rocks, and diluted with about 25 to 50% meteoric water. An exception was the first production from well HGP-A, which was a much more dilute Na-Cl composition, resembling meteoric water altered in basalts, possibly including a small altered-seawater component. During its history, the fluid from well HGP-A shifted slowly but progressively to the altered-diluted-seawater signature.

The sequence of seawater hydrothermal reaction and dilution is not easily established: it is uncertain whether seawater becomes diluted and then reacts with hot rocks, or if dilution follows the principal hydrothermal reactions. Reaction followed by dilution probably is the dominant process. Some dilution undoubtedly occurs during mixing of wellbore fluids of different salinities.

There are strong chemical gradients in the reservoir. At well HGP-A, the earliest production had an average pre-flash reservoir-liquid Cl of about 1,700 ppm, whereas the Cl level by 1984 was over 7,000 ppm. The increase in Cl occurred between 1981 (first steady production) and 1985, and the concentration of Cl from the well was stable after that time. The increasing Cl was accompanied by the shift from meteoric-hydrothermal to seawater-hydrothermal character.

Horizontal gradients also exist. In contrast with the >7,000 ppm Cl at well HGP-A, Cl values are 12,000 to 14,000 ppm at KS-1A, about 17,000 ppm at Lanipuna 1, and 15,500 ppm at Lanipuna 6. These in turn compare with 19,000 ppm Cl in seawater. From wells KS-2 and KS-3 there are reports of over 40,000 ppm Cl in brine flashed to the atmosphere. The brine flow rates were apparently very small, and the steam flow rate high, such that the brine probably suffered excessive evaporation: this is the most likely explanation for the very high Cl at both wells. However, the data allow that a concentrated brine may be present deep within the reservoir.

From geothermometry, the average chemical temperatures of the reservoir waters are as tabulated below.

Average Temperature, °F

Well	SiO_2	Na-K-Ca	Na-K	Measured
HGP-A (November 1982)	555	490	510	~560
HGP-A (November 1984)	555	460	470	
KS-1A	575	560	600	~625
KS-2 (1 sample)	n.a.	545	585	
KS-3 (1 sample)	n.a.	550	576	
Lanipuna 1	320	440	440	~320
Lanipuna 6	265	345	330	

SiO_2 temperatures represent the quartz, adiabatic geothermometer at wells HGP-A and KS-1A, and the chalcedony, conductive geothermometer at Lanipuna 1 and Lanipuna 6. Measured temperatures are the probable temperature of the main production zone at HGP-A and KS-1A, determined from temperature and spinner logs, and the temperature at a fracture which is believed to be the source of production in Lanipuna 1.

As shown above, the quartz, adiabatic temperatures of samples from well KS-1A are about 575°F, compared to a probable reservoir temperature of about 625°F. The low quartz temperatures suggest that either (a) the liquid portion of production comes from a cooler zone in

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the well, above the 625°F production zone, or that (b) silica was lost prior to sample collection. Either cause is possible. Note that the reservoir temperature near the top of the slotted liner in well KS-1A is about 580°F. This suggests that the silica temperature is correct, that the 625°F reservoir zone mostly produces steam, and that the water produced by the well mostly comes from near the top of the liner.

Figure 5.2 shows Na and K concentration in all water samples. This table also illustrates the relative Na/K temperatures for these deep wells, based on the relationship in which water-rock reactions cause Na/K to decrease as temperature increases. At well KS-1A, the cation temperatures Na/K and Na-K-Ca both agree fairly well with the quartz and measured temperatures.

At HGP-A the cation temperatures are distinctly low, and Na/K has increased over time. This suggests that the more-saline water which has been drawn into the well comes from a lower-temperature regime and has not completely equilibrated to conditions near the well. During the production of well HGP-A after 1981, its SiO_2 concentration remained constant, and SiO_2 temperature averaged 555°F, in spite of the increase of Na/K. This suggests that near-wellbore temperatures remained high. Na-K temperatures declined from about 510°F in November 1982 to 470°F in November 1984.

Regardless of the accuracies of the chemical temperatures, the relative temperatures at each well are consistent with measured temperature gradients across the reservoir. The temperature is highest at KS-1A, grading outward and down to KS-2 and KS-3, HGP-A, Lanipuna 1, then Lanipuna 6.

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5.2.3 Non-Condensible Gases

At well HGP-A, non-condensible gases (NCG) in steam changed only slightly during production since 1981. Concentrations were as follows, showing the concentration in steam at initial production (1981) followed by the concentration 3-1/2 years later:

Species	ppm-wt
CO_2	1,250/1,150
H_2S	950/850
N_2	130/120
H_2	12/12
CH_4	1/no data
total NCG	2,340/2,130

These concentrations were determined in steam separated at a typical pressure of about 155 psig.

At well KS-1A, the gases in steam also determined at about 155 psig, are:

Species	ppm-wt
CO_2	230-320
H_2S	1,200
total NCG	2,000-2,200

Reliable data on gases at KS-1 and KS-2 have not been found.

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The CO_2/H_2S ratio in these gases is quite low compared to typical values in geothermal systems worldwide, and H_2S/steam is much higher than found in typical water-dominated systems. The unusual CO_2/H_2S ratio and high H_2S probably are related to the recent magmatic activity in the Puna area, and/or to reactions between seawater and reduced iron in hot basalt, which could reduce seawater sulfate to sulfide.

5.3 Hydrogeology

The present hydrogeologic model was developed by: a) plotting the three-dimensional distribution of temperature and pressure; b) using these data to define flow paths in the system; and c) relating these flow paths to permeable geologic structures.

The three-dimensional temperature distribution in the Puna field was determined by:

a) plotting all the downhole temperature surveys available for the Lanipuna, KS, HGP-A and SOH wells (Appendix A);

b) interpreting the survey data to determine the most-likely rock-temperature profile in each well;

c) plotting the interpreted data on subsurface-level maps at depth intervals of 1,000 feet, to show the horizontal distribution of temperature though the drilled depth of the field; and

d) constructing cross-sections to show the vertical distribution of temperature.

5.3.1 Interpretation of Temperature Logs

The temperature logs from the Puna wells are shown on downhole summary plots (Appendix A). The summary plots include: depth data converted to elevation (feet above or below sea level); information on well completions; location of lost-circulation zones; and drilling rates and/or spinner survey data. The rock temperatures interpreted from these surveys are listed in table 5.2.

Lanipuna 1

Although the maximum undisturbed period of well heating-up prior to temperature logging was only 56 hours, the general trend and slope of the gradient is the same in six of the logs (excluding the log taken one day after air-lifting the well). Because of this relative uniformity of slope, true rock temperatures were interpreted to fall on a line drawn through the highest measured temperatures at 3,000 feet and 5,600 feet, in depth, and parallel to the slope defined by all the curves. The temperatures between -1,000 and -7,000 feet (msl) resulting from this interpretation are given in table 5.2.

Lanipuna 1 Sidetrack

The temperature gradient measured between 4,400 and 5,100 feet in depth on 18 July 1983 was projected upward to 3,000 feet in depth, in order to estimate the true rock temperatures at -3,000 and -4,000 feet (msl). The temperature reversal below 6,000 feet in depth was assumed to be real because it persisted through 28 days of heating time in a zone where no loss of circulation was noted. A temperature of 330°F was projected for -6,000 feet (msl).

Lanipuna 6

Between -1,000 and -3,000 feet msl, true rock temperatures were interpreted to fall on a line drawn between the temperature measured at -1,000 feet (msl) 16 hours after pumping (7 August 1984), and the maximum temperature measured at -3,100 feet (msl) after 53 days of heating. The temperature reversal below -3,800 feet msl is considered to be real, because it persists for 600 feet below the lost-circulation zone at -3,800 feet (msl).

HGP-A

The temperature profile measured on 8 March 1977 (well undisturbed for 25 days) was interpreted to most closely represent the true rock temperature. This profile is in good agreement with profiles measured on 4 December 1976 and 3 January 1977, which were done after relatively long undisturbed periods. The high temperatures measured between 4,000 and 5,500 feet in depth in the logs of 22 and 29 July and 4 August 1976 are considered to be influenced by recent production; therefore, they are not representative of the true rock temperature.

KS-1

Only the temperature measured at 1,600 feet in depth, after a cement plug was set at 1,750 feet in depth, was used from the profiles measured in this well. Temperatures measured between 1,800 and 3,600 feet in depth are consistently lower than those measured 100 feet away in well KS-1A, and therefore, are considered to be unstable.

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KS-1A

In spite of the relatively large number of temperature logs measured in this well, the temperature data are the most difficult to interpret of all the wells. All logs run after 8 November 1985 show temperatures in excess of 550°F at 2,000 feet in depth, which is considered to be unrealistically high for this depth. These unusually high temperatures probably are caused by the convection of two-phase fluid (the temperature data from these profiles fall on a boiling-point-for-depth curve) *i.e.* suggest circulation in the wellbore.

The log run on 6 November 1985 (six days of heating after production testing) agrees with the temperatures measured above the cement plug at 1,750 feet in KS-1 (almost 200°F); but still appears to be influenced by the recent production testing below this point. On the other hand, the profile run on 11 September 1985 (heating for five days after injection) appears to be cooler than the true rock temperature.

Because of this lack of stabilized profiles, a smooth curve was drawn between 174°F at -1,000 feet (msl) and 580°F at -4,000 feet (msl) to approximate the temperatures between these elevations. The lower point corresponds to an inflow zone on the 11 September 1985 profile. True rock temperatures appear to correspond to a boiling-point-for-depth curve between 5,500 feet in depth and bottomhole; this curve was used to estimate temperatures at -5,000 and -6,000 feet (msl).

KS-2

Temperatures measured in this well also are affected by the two-phase convection of fluids within the well and, consequently, profiles measured on 4, 17, 24 and 29 April 1982 probably do not reflect

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the true rock temperatures. The profile or 14 June 1983 was run five months after setting a cement plug at 3,175 feet in depth; temperatures measured on that log at -1,000 and -2,000 feet (msl) are considered to be correct, because it is unlikely that convection could occur above the plug.

Between 3,700 and 5,000 feet in depth, temperatures measured on the combination of profiles dated 1, 14 and 17 April 1982 were considered to be closest to the true rock temperature. Temperatures at -5,000, -6,000 and -7,000 feet (msl) were assumed to fall on a slightly curved line connecting the 520°F temperature measured at -4,000 feet (msl), and a projected bottom hole temperature of 690°F. The bottomhole temperature was projected from a boiling-point-for-depth curve drawn through the profile of 24 April 1982.

SOH-1

The data on the downhole summary plot in Appendix A include five temperature surveys run in well SOH-1 between 5 January and 1 March 1991. The four surveys conducted before and after the injection test of 10 January 1991 cannot be considered to reflect full temperature stabilization. The fifth survey, taken on 1 March 1991, 49 days after the injection test, is considered to be fully stabilized.

The temperature profiles show clearly the fractured zone where the injected water entered the formation at depths between 4,180 and 4,220 feet. From 4,500 feet to total depth (5,526 feet), a conductive gradient of approximately 25°F per 100 feet was measured. A blockage in the well, possibly caused by drilling mud left in the well after its completion, prevented the last two surveys from being run below 5,160 feet.

SOH-2

Temperature surveys (Appendix A) show the presence of a conductive gradient in the open-hole section, on the order of 14°F per 100 feet from a depth of 4,750 to 6,800 feet. This is similar to the gradient measured in well SOH-1, but much lower in value. There also appears to be a permeable zone below the 4-1/2-inch casing shoe (between 4,200 and 4,900 feet), where temperatures range from 280°F to 420°F. Below 4,900 feet in depth, the temperature profiles measured during both injection of cold water and under static conditions are similar, indicating that very low permeability exists throughout this part of the open interval. Most of the injected fluid leaves the well between the casing shoe and 4,900 feet. The maximum temperature measured in well SOH-2 is 661°F, at 6,782 feet.

SOH-4

As shown in the downhole summary plot in Appendix A, a temperature survey was run 234 days after injection. It can be assumed that the well had reached temperature stabilization; the maximum temperature measured at 6,463 feet was 576°F.

A possible entry of injected fluids can be observed directly from the surveys at depths between 2,400 and 3,650 feet. No entry of injected fluids seem to have occurred below 3,650 feet. A sharp increase in temperature is observed on all logs at 4,550 feet. Below this depth, all surveys indicate a conductive gradient of the order of 10°F per 100 feet.

5.3.2 Subsurface Temperature Distribution

Temperature contour maps (figures 5.3 through 5.8) have been prepared for each 1,000-foot-elevation interval between -1,000 and -6,000 feet (msl), based on the interpretation of the temperature logs described above. Table 5.2 lists the temperatures chosen for contouring for each well at each elevation interval.

The kick-off-point for well Lanipuna 1 Sidetrack is at 3,570 feet in depth. Therefore, the points of measurement of temperatures at the -1,000, -2,000 and -3,000 foot levels are the same for both the original hole Lanipuna 1 and 1 Sidetrack. Nevertheless, because of disequilibrium conditions, temperatures are not in agreement between the two series of logs taken over this interval, as can be seen in table 5.2. The temperatures given at -5,000 feet (msl) for well Lanipuna 6, and at -6,000 feet (msl) for HGP-A, KS-1 and -1A are projected downward from shallower measurements.

Figures 5.3 through 5.8 show the interpreted temperature distribution for levels -1,000 through -6,000 feet (msl), respectively. At -1,000 feet (msl), well HGP-A is in the highest-temperature area, with temperatures decreasing to the north, south and east. There are insufficient data to close the contours to the west. This pattern remains the same at -2,000 feet (msl).

At -3,000 feet (msl), although HGP-A is still the hottest well, temperatures in the KS wells are significantly hotter compared to higher levels. At -4,000 feet (msl), KS-1A is the hottest, and temperatures decrease uniformly to the southeast. This pattern is repeated on the -5,000 and -6,000 foot (msl) levels, with the addition of a relatively low-temperature zone around well Lanipuna 1 Sidetrack developing on the -5,000 and -6,000 foot (msl) levels.

On the -1,000 and -2,000 foot (msl) levels, the axis of symmetry of the temperature anomaly trends within 10° of the direction of the rift fractures (N60°E). However, the axis of symmetry of the anomaly is displaced 1,000 to 1,500 feet to the southeast of the main fissure zone. The spatial relationship of surface geology with the temperature anomalies developed on the -1,000 and -2,000 foot (msl) levels therefore suggests that the anomalies are caused by thermal fluid moving on fractures parallel to, but to the southeast of, the main rift fracture.

On the -3,000 foot (msl) level and below, the well data define an axis of symmetry less than 1,000 feet southeast of the main fissure zone. It is also likely that the anomaly below -2,000 feet (msl) is due to fluid movement along rift fissures.

The SOH well data imply that the patterns developed on the -3,000 to -6,000 foot (msl) levels are caused by fluid movement from southwest to northeast in the main fissure zone. Therefore, there exists on the northwest side a mirror image of the temperature pattern developed from well data on the southeast side of the main fissure. This interpretation is illustrated in figures 5.5 through 5.8 by contouring the temperature pattern defined by well data on the southeast side of the main rift fissure with solid lines, and by contouring the inferred, mirror-image pattern on most of the northwest side of the fissure with dashed lines.

Projection of a mirror-image temperature pattern to the northwest side of the fissure implies that the geology, and therefore the permeability distribution, are the same on each side of the fissure. This may not be true, because the active fissures within the KERZ are located at the southern boundary of the dike complex which forms the rift. The permeability pattern north of the fissure may be influenced by the presence of steeply-dipping dikes, which are less likely to be present on the south side of the fissure.

Additional subsurface temperature data is needed from the north side of the fissure, in order to confirm or modify the temperature patterns proposed in figures 5.3 to 5.8, which have been drawn on the assumption that the geology on the northwest side of the fissure is similar in detail to that found on the southeast side.

A vertical section drawn perpendicular to the northeast trend of the anomaly is shown along line A - A′ in figure 5.9. The margins of the rift zone are shown, as are the projected traces of nearby wells for the reader's convenience. This section is constructed from a series of horizontal sections (maps of temperature distribution) that are constructed at selected depths. The section has no vertical exaggeration; consequently it illustrates the relative flatness of the anomaly above -3,000 feet (msl), and the steepness of the sides of the anomaly below this elevation. However, temperature data from wells KS-7 and -8 may alter this configuration, if the wells have intercepted projections of high temperature at shallow depths. Structural elements that may result in local and linear temperature apophyses are consistent with the proposed conceptual model.

As stated above, this steepness indicates the control of flow paths by steeply-dipping fissure zones. At higher levels (above -3,000 feet msl), the flow paths appear to be modified by stratigraphic permeability and/or a southeastward component of ground-water movement.

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This would account for the temperature reversal seen in well Lanipuna 6 as shown on the south side of section A - A′ (figure 5.9). The relatively cold zone in well Lanipuna 1 Sidetrack appears to be an artifact of another steeply-dipping hot zone developed along the main fissure zone, which apparently is offset to the southeast of the drilled area.

5.3.3 Pressure Distribution

Information on pressure gradients is available for seven wells (figure 5.10 and table 5.3): Lanipuna 1 Sidetrack, HGP-A, KS-1A, KS-2, SOH-1, SOH-2 and SOH-4. These data are plotted on the downhole summary plots (Appendix A). Pressures recorded (or projected) to the common datum of -5,000 feet msl are given in the second column of table 5.2, and the pressure gradients recorded between -4,000 and -5,000 feet (msl) are given in the third column. These elevations are coincident with lost-circulation intervals.

The pressure values at the -5,000-foot level are contoured on figure 5.10. It shows that the orientation of the isobars is similar to the orientation of the isotherms at this same level. That is, pressure increases uniformly to the southeast, while temperature decreases uniformly in the same direction. The horizontal-pressure gradient is 600 psi over a distance of 2,000 feet (0.3 psi/foot). This gradient indicates there is a horizontal component of flow from southeast to northwest at the -5,000 foot level. Horizontal pressure gradients as large as those observed clearly reflect reservoir conditions rather than artifacts of perturbations resulting from internal flow. The location and orientation of the isobars suggests that this flow is feeding upward convection on the main fissure. This is compatible with the interpretation that flow within the fissure is responsible for the temperature pattern seen on levels -3,000 through -6,000 feet.

The relatively low vertical pressure gradients measured in the KS wells, as compared to the gradients measured in HGP-A and Lanipuna 1, also support the interpretation that upward convection is taking place on the main fissure zone, because the KS wells are located adjacent to the fissure. The logs of the lower parts of these wells indicate that temperatures, indeed, are on the boiling-point-for-depth curve.

5.3.4 Summary of Conceptual Model

The conceptual model developed herein is based upon the most straight-forward interpretation of rift geology and down hole measurements. The model explains all available observations. The characteristics of the conceptual model for the geothermal system are as follows:

1. The shallow, cool ground-water system is not well defined by pressure and temperature measurements. It is clear that fresh water enters open fractures at the northern and southern margins of the rift zone, but penetration rate and depth are less clearly known. The cold-water gradient would be generally from NNW to SSE.

2. Leakage from the geothermal reservoir into the shallow system occurs within the KERZ, but appears to be limited in areas outside the KERZ.

3. The increase of temperature to the northwest within the drilled areas, and the strong horizontal temperature gradient (6°F per

100 feet), indicate that thermal fluid is being channeled along steeply dipping structures within the KERZ paralleling the NE-trending 1955 eruptive fissure.

4. By assuming that temperatures are developed symmetrically on both sides of the fissure, the resulting temperature pattern suggests that a horizontal component of flow is directed from southwest to northeast, parallel to the trend of the KERZ.

5. A strong horizontal pressure gradient of 0.3 psi/foot parallels the temperature gradient, indicating relatively poor horizontal permeability in the NW-SE direction, and supports the conclusion that flow is dominated by steep, NE-trending structures.

6. The presence of temperature profiles on the boiling-point-for-depth curve in the deeper parts of the KS wells indicates that steam-water counterflow is occurring close to the fissure.

7. Based on the structure of older rift zones exposed elsewhere in the Hawaiian Islands, it is probable that the zones of steep permeability are related to tensional fracturing during dike emplacement. The tensional fractures are likely zones of greater permeability and targets for geothermal wells within the geothermal reservoir. The dikes which form rift zones are individually only a few feet wide, dip from 90° to 70° and, in densely intruded areas, are spaced only a few feet apart.

8. A transition zone from subaerial basalt flow to submarine (pillow) basalt flows at depths between ~2,800 to ~3,400 feet is also characterized by hyaloclastite rocks and perhaps by

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pervasive hydrothermal alteration to a cap rock. An imperfect seal occurs, and thermal fluids leak upward along steep fractures. The transition zone has been found at greater depth (below 5,000 feet) in hole SOH-4; additional data from wells KS-7, -8 and KMERZ A-1 will be particularly valuable in assessing the effects on the geothermal system.

9. The deep thermal fluid is a mixture of fresh water and seawater, with the seawater component apparently increasing to the southeast, away from the fissure zone. This suggests that recharge to the system may be mainly meteoric in origin; significant seawater recharge may be induced into the deep reservoir if wells are produced to the southeast of the fissure zone.

10. Although various warm springs occur along the coast southeast of the drilled area, the absence of large hot springs indicates that lateral discharge from the zones of steep permeability in the subsurface may be limited. The basal ground-water level is just above sea level, and well GTW-3 found near-boiling temperatures at sea level just northeast of the drilled area. The thin (100 foot thick), high-temperature zone indicates the presence of lateral discharge on top of the local cold-water table.

11. Large volumes of cold ground-water move through shallow aquifers and cause rapid decline of temperatures observed in drill holes at the NNW and SSW margins of the geothermal reservoir area.

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This conceptual model of the hydrologic system is likely to change in detail as more information is obtained from existing and future deep wells. However, there is no excuse to delay presentation of the model based upon "complexities" of the system, and await performance of additional surveys, studies and other investigations.

It is particularly important that downhole temperatures and pressures are measured accurately in new wells. All flow tests should be run by knowledgeable professionals to assure the greatest measures of safety as well as precision in measurement, sampling techniques, recording of information, timely interpretation and reporting. All new information should be acquired by the State in keeping with regulations.

The State's SOH holes should be designed and drilled to acquire temperature, pressure and interference data. Future holes of the SOH series should be permitted for flow tests, to obtain productivity data and fluid samples for chemical analyses.

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6. QUANTITATIVE RESERVOIR EVALUATION

The history of drilling and testing of wells in the KERZ, and their current status, are discussed in Chapter 4. In the present Chapter, well behavior and well-test data are analyzed and quantified to the degree possible, as part of the estimation of reserves of geothermal energy in the KERZ. Data on the drilling history of each well are summarized in table 4.1 and in Appendix A.

6.1 Analysis of Well-Test Data

6.1.1 KS-1

Well KS-1 was completed on 10 November 1981 to a total depth of 7,290 feet. The downhole summary plot in Appendix A includes well completion details and available temperature and pressure surveys. Although the temperature surveys probably do not reflect true rock temperatures at the indicated depths, they do indicate reservoir temperatures in the range of 625°F to 650°F. Permeable zones occur at a number of intervals between 5,000 and 7,200 feet in depth.

The initial flow test was conducted for 45 minutes on 16 December 1981, using a James tube discharging into a twin-tower silencer. Following this test, a leak was found in the 9-5/8-inch production casing. A 7-inch liner was therefore cemented from surface to 1,898 feet in May 1982, and the well was re-tested, first using a James tube for 30 hours, and then using a pressure separator for 293 hours during August 1982.

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During the separator test in August 1982, the well was found to produce dry steam. The discharge data are summarized in table 6.1 and plotted in figures 6.1 and 6.2. At the wellhead pressures required for the PGV power plant, the well was capable of initially producing 3.2 MW.

On 18 February 1983, a temperature survey was conducted while injecting cold water in the well, because it was believed that a second leak had developed in the cased section. The survey (see Appendix A) shows a very rapid increase in temperature from 134°F to 557°F between 660 to 680 feet, suggesting that the injected water was leaving the well through a casing leak at this depth.

6.1.2 KS-2

Well KS-2 was completed on 28 March 1982 to a total depth of 8,005 feet. The downhole summary plot of temperature and pressure surveys (Appendix A) indicates that the well encountered somewhat higher temperatures than well KS-1; temperatures range from 600°F to over 670°F in the open interval. Below the production shoe, permeable zones occur from 5,000 feet to 7,200 feet in depth.

The well was flow-tested several times during April to August 1982. The most-reliable data were collected when the well flow was directed to a pressure separator, during 28 July to 2 August 1982. In that test, the well produced essentially dry steam at high wellhead pressures, and wetter steam at wellhead pressures below 160 psia. It was believed that the variation in steam wetness with wellhead pressure was due to a casing leak, located by means of temperature surveys at approximately 1,000 to 1,100 feet in depth. These surveys are not shown on the downhole summary plot; however, a later survey, conducted on 25 January 1983, also indicates a possible casing leak at that depth.

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The well-discharge data are included in table 6.1 and plotted in figures 6.1 and 6.2. It can be seen from figure 5.2 that the well was capable of producing approximately 1.0 MW. This is barely one-third the capacity of well KS-1. However, it is thought that constrictions in the wellbore may have significantly lowered the true potential of the well; 2 MW is assumed as the possible capacity of an undamaged well.

6.1.3 KS-1A

Well KS-1A is located 100 feet south of KS-1, and was completed on 3 September 1985 to a total depth of 6,505 feet. Downhole summary plots (Appendix A) indicate that the temperature reached approximately 670°F at bottomhole.

KS-1A was tested through a pressure separator from 7 to 31 October 1985. The raw test data have been analyzed, and the calculated flow rate and enthalpy are plotted as a function of time in figure 6.3. The variation in measured wellhead pressure with time also is shown. Using the calculated production data, the variations in flow rate, enthalpy and power-output-with-wellhead-pressure are plotted in figures 6.4, 6.5 and 6.6, respectively. The data also are summarized in table 6.1.

Flow data from KS-1A show that the well can produce approximately 3.0 MW at the required wellhead pressure for the PGV plant. This is similar to the output from KS-1, but unlike KS-1 and -2, well KS-1A produces a two-phase mixture of approximately 75% steam and 25% water. The constant-discharge enthalpy, measured while flowing at low wellhead pressures, also suggests that the well encountered higher permeability, resulting in less reservoir drawdown than in wells KS-1 and -2. It is thought that the production of dry steam in the other two wells reflects excessive drawdown caused by limited permeability, rather than the presence of naturally occurring steam zones in the reservoir.

At high wellhead pressures, the discharge enthalpy decreased (figure 6.5), which is interpreted to indicate that flow from an upper two-phase zone in the well is being restricted. However, the high wellhead-pressure data were collected only during a two-day period; therefore, the measured enthalpies are not considered to be stable. The true stable enthalpies are probably lower than the measured values.

During the flow test, a downhole spinner was run; the spinner data, discussed in Chapter 4.2 and included in the downhole summary plot (Appendix A) demonstrate shallow (4,500 to 5,500 feet) and deep (below 6,300 feet) flow zones. A temperature survey conducted seven hours after well shut-in showed significant cooling between 5,400 and 6,300 feet; this condition is thought to be related to the two-phase flow of steam and water from the reservoir into the well.

Attempts were made to measure the reservoir flow capacity (transmissivity or "kh") in the vicinity of the well, by conducting an injection test followed by a pressure-falloff test and a pressure-buildup test. The injection test indicated an injectivity index of 1,100 pounds per hour per psi (lbs/hr/psi), which is average for a geothermal system of this type. The pressure-falloff data could not be analyzed, because of non-isothermal effects and associated density changes in the well. The pressure-buildup data appear to be affected by internal flows within the well. Internal flows also may have caused the cycling in wellhead pressure that was noted after the well was shut in.

In an attempt to measure possible interference with surrounding wells, water-level measurements were taken at the Malama Ki and Airport

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wells before, during and after the flow test. These wells are located approximately 1.5 miles SSE and about 2.5 miles northwest of KS-1A, respectively. No change in water level was measured. The large distances between the wells and the large differences in completion depths make these results predictable. The discharge parameters at well HGP-A were also closely monitored for any changes due to the discharge of KS-1A, but no measurable effect was detected.

6.1.4 KS-3

Well KS-3 was drilled to a total depth of 7,406 feet during 1990-91 by PGV. However, during the final trip of the drillpipe, in January 1991, the pipe stuck at bottomhole. It was finally necessary to leave the stuck pipe inside the well and, on 21 January 1991, the slotted liner was run to 6,835 feet. An injection test was run at well completion, and the well was then left to heat up in preparation for a flow test. The flow test was delayed because of problems encountered during the drilling of KS-7, and was not conducted until 25 to 31 March 1991. Temperature surveys conducted prior to the discharge test indicated that the maximum downhole temperature was 664°F.

The flow test started at 1300 hours on 25 March with the well being vented vertically to the atmosphere for 3 hours. The well was then shunted to the flow-test facility, which included a pressure separator and the necessary instrumentation for monitoring pressure, temperature and flow rate. H_2S abatement equipment was also installed.

During the flow test, the wellhead-pressure conditions ranged from a low of 103 psia to a high of 615 psia, and the total flow rate varied from 70 to 90 KPH. The measured data are summarized in table

6.1, and flow rate and enthalpy are plotted as functions of wellhead pressure in figures 6.7 and 6.8. The calculated power output at a separator pressure of 225 psia is plotted as a function of wellhead pressure in figure 6.9. This figure indicates that the well is initially capable of producing approximately 3.2 MW. This is similar to the output of wells KS-1 and -1A.

Well characteristics also are similar to KS-1A in that (a) the well produces a two-phase flow of steam and water and (b) the enthalpy decreases with increasing wellhead pressure. Comments made regarding reservoir conditions at KS-1A also are presumed to apply for KS-3.

During the flow test of KS-3, a number of temperature and pressure surveys were run. These indicated that fluid was flashing in the reservoir, and a two-phase mixture of steam and water was entering the well. Pressure drawdown at the bottom of the well was approximately 560 psi, which is very high considering the relatively low total flow rate.

A pressure-buildup test then was conducted; the Horner semi-log plot of the data appears as figure 6.10. The plot suggests that data were not collected for a sufficient period of time to define the semi-log straight line, and therefore three possible matches are shown. However, the kh values range only from 240 millidarcy-feet (md•ft) to 750 md•ft, while the skin factors range from -2.7 to 4.3. These values of kh are very low for geothermal reservoirs, but are consistent with the measured pressure drawdowns and total flow rates.

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6.1.5 SOH-1

SOH-1 was the second hole drilled under the State of Hawaii's scientific observation and evaluation program. It was completed on 6 January 1991, to a total depth of 5,526 feet. Because the scientific observation holes did not have permits for discharge testing, activities were limited to injection testing and conducting downhole temperature and pressure surveys. The maximum temperature measured was 408°F at 5,500 feet, 24 hours after completion. This is significantly lower than temperatures measured at comparable depths in the PGV wells just to the south.

SOH-1 was cooled for several days during the completion operations by injection of a constant flow of water; approximately 18 gpm was injected for approximately 12 hours prior to the injection test. On 10 January 1991, two Kuster tools equipped with 12-hour clocks were hung at 3,075 feet to record the well's downhole pressure response throughout the test.

The drilling rig's Gardner Denver duplex pump, with an operating pressure limit of approximately 350 psi, was utilized for water injection. The first and second injection-rate steps were kept at constant levels of 80 and 110 gpm, respectively, for periods of approximately 90 and 105 minutes. A total volume of 20,170 gallons was injected during the test. The injection history is shown in figure 6.11.

The pressure falloff after injection was observed for a period of approximately 75 minutes. Interpretation of the Kuster charts showed that after this period the downhole pressure had dropped to within 2% of

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the initial pressure; therefore it was not necessary to run a second Kuster tool to continue monitoring the pressure falloff.

Figure 6.12 shows the Horner plot of the downhole pressures measured during monitoring of the pressure falloff. This is a standard technique used in well-test analysis to estimate kh and skin factor. The plotted data show the end of wellbore-storage effects at a Horner time of approximately 13. By definition, the small values of Horner time correspond to large shut-in times, and a Horner time of 1 corresponds to an infinite shut-in time. After the wellbore-storage period, a semi-log straight line can be approximated through the data points. Using the slope of the semi-log straight line and the injection flow-rate history, the kh is calculated to be 6,100 md•ft. From the observed pressure-change behavior and the Horner line, the well skin factor is estimated to be +39.

The value calculated for kh is considered to be relatively low, and the positive value of skin factor indicates some type of flow restriction in the near-wellbore region.

During drilling, intermittent losses of circulation were reported below 3,900 feet; the volume of the losses increased to nearly total between 4,150 and 4,200 feet. Below this level, the loss gradually healed itself to a condition of nearly full returns by the end of drilling activities. No use of cement or lost-circulation material was reported while drilling through the loss zone. Temperature surveys run before and after the injection test (Appendix A) also confirm that most of the fluid was injected into a fractured zone between 4,180 and 4,220 feet. The possible sealing of the permeable zone during the continued drilling may provide an explanation for the very high skin factor.

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The values of kh and skin factor calculated from the Horner analysis were in turn used to calculate the theoretical reservoir response to the injection flow history (figure 6.11). The theoretical response is compared with the measured response in figure 6.13. A very good match was obtained, confirming that the results of the Horner analysis provide reasonable estimates of the reservoir hydraulic properties.

6.1.6 SOH-2

SOH-2 was completed on 4 June 1991 to a depth of 6,802 feet. The maximum measured temperature, on 6 June 1991, 2 days after the well had been drilled and prior to its injection test, was 661°F. Both partial and total losses of circulation were recorded while drilling.

Between 6 and 8 June 1991, a series of temperature logs was run in the well, under static conditions and while injecting cold water at various rates. The surveys are included on the downhole summary plot in Appendix A.

On 8 June, after running the third temperature survey, two pressure tools equipped with 12-hour clocks were run into the well to 4,500 feet. A total of 23,000 gallons of water was pumped into the well over a period of 3 hours at basically two different pumping rates (figure 6.14). After stopping injection, the tools were left inside the well for 9 additional hours to record the pressure falloff.

Figure 6.15 shows the Horner plot of the measured downhole pressure data after injection was stopped. It shows two possible straight lines, between a Horner time of 3 and 40 and at the end of the data (Horner time of less than 2).

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The straight line shown on the Horner plot on figure 6.15 is believed to be the correct line for estimating kh, whereas the shape of the pressure response is characteristic of either a fractured formation or double-porosity behavior. We have therefore used a double-porosity model to analyze the test data.

Analysis of the pressure-falloff data provides a kh estimate of 1,300 md•ft and a well skin factor of -0.2. The kh value is very low but is consistent with the level of pressure change caused by the injection flow rates.

The values of kh and skin factor estimated from the pressure-falloff data were then used to calculate the theoretical response to injection, and this is compared with the measured response in figure 5.16. A reasonable match is obtained to the measured data, indicating that the reservoir parameters are reasonable. The low value of flow capacity is also consistent with the conductive gradient observed in temperature surveys of SOH-2 (Appendix A).

6.1.7 SOH-4

SOH-4 was completed on 20 May 1990 to a total depth of 6,562 feet. Partial and total losses of circulation were observed during drilling. Drilling of the lower portion of the well was conducted using a polymer mud system, which degrades rapidly with increasing temperature and breaks down after the well has been completed. This mud system was used to ensure that mud-cake buildup in the permeable zones would not affect the well permeability during testing.

A series of temperature and pressure logs was run in the well between 21 and 23 May, under static conditions and while injecting cold

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water at various rates. The surveys consisted of continuous-readout temperature and spinner surveys, as well as several logs run using Kuster tools. As seen on the downhole summary plot (Appendix A), the maximum measured temperature was approximately 580°F.

To quantitatively assess the permeability of SOH-4, an injection test was conducted while monitoring the pressure changes at 5,000 feet with the Kuster pressure tool. It was originally planned that a multi-rate injection test would be conducted, with monitoring of the downhole pressures during both the injection and recovery phases. The test was started at 2231 hours on 21 May, with an initial injection rate of 30 gpm. The Kuster tool, with a 12-hour clock, had been set at 5,000 feet before injection began. The flow rate was increased to 60 gpm at 0012 hours, 22 May and this was continued until 0112 hours when pumping was stopped. The Kuster tool was retrieved at 1033 hours, but it was found that the clock had stopped during the survey. Hence, no pressure-recovery data were measured.

With the failure of the 12-hour clock, it was decided to run an abbreviated injection test using the remaining 3-hour clock. The test started at 1340 hours, 22 May and included pumping at 60 gpm for one hour, followed by monitoring of the pressure recovery for two hours. This test was carried out successfully, and good-quality pressure data were obtained.

However, when the pressure-transient data were analyzed, it was found that the test duration was too short to accurately reflect the true reservoir response. It was therefore not possible to quantitatively assess the reservoir hydraulic properties, although the results did suggest qualitatively that the well was relatively tight. It was decided to conduct a second test on the well.

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The second injection test was conducted after the completion of SOH-1 on 12 January 1991. To enhance the test results and avoid well damage by thermal shock, it was necessary to cool down the well, initially by injecting at a very low rate of approximately 10 gpm for a period of about one hour (figure 5.17). The flow rate was then increased to about 80 gpm for a further period of 85 minutes. After this period, the pressure tools were hung at the depth of 4,500 feet.

A two-rate injection test then was run, with average injection flow rates of 147 and 230 gpm, respectively, for periods of approximately 204 and 171 minutes. A total volume of 68,700 gallons was injected during the test. The pressure falloff after injection was observed for a period of approximately 235 minutes.

Initial interpretation of the Kuster charts showed that, after this period, the downhole pressure was dropping at a rate lower than 0.1 psi in 30 minutes; therefore, it was not necessary to continue with the pressure-falloff observation.

Figure 6.18 shows the Horner plot of the downhole-pressure data measured in SOH-4 after the two-step injection test. The plot shows that the pressure-falloff measurements were taken for a sufficient length of time to clearly reveal the semi-log straight line, after the wellbore-storage effects had concluded.

The Horner analysis gives a calculated kh of 1,360 md•ft, and well skin factor of -2.4. The negative value for the skin factor probably reflects that the wellbore has intersected a fractured formation.

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These estimates of kh and skin factor have been used to calculate the theoretical response to the injection history, and this is compared with the measured response in figure 6.19. The falloff data have been reasonably well matched, as is to be expected, but the well's pressure response during injection cannot be matched using the same hydraulic parameters: the apparent measured response to flow-rate changes is not as great as the calculated response would suggest. In view of the very good matches obtained for wells SOH-1 and SOH-2, it is difficult to explain why the match is not good for SOH-4, unless the flow-rate measurements are not reliable. The value of kh is consistent, however, with the result from SOH-2, indicating a very low reservoir flow capacity.

6.2 Reservoir Characteristics Inferred from Well-Test Data

Of the eight deep wells tested to date, five (HGP-A, KS-1, KS-2, KS-1A and KS-3) have undergone discharge tests for varying time periods. These five wells have remarkably similar outputs, estimated to be in the range of 2 to 3.5 MW. Limited pressure transient data from HGP-A and KS-3 indicates that the reservoir has a very low reservoir flow capacity, on the order of 1,000 millidarcy•feet (md•ft). However, the wells are still able to produce at commercial flow rates and well head pressures because of the very high reservoir temperatures which average approximately 650°F.

These five wells are located in the same area of the KERZ (figure 6.22); however, additional reservoir data is available from SOH-1, -2 and -4 drilled during 1990 and 1991. These wells are located both to the east and west of the more-developed area. There were also indications of significant fluid entries in the drilling reports from the KMERZ A-1. In addition to KMERZ A-1, wells KS-7 and -8 had strong indications of productive geothermal zones.

Injection tests followed by pressure-falloff tests were used to estimate the reservoir properties of the SOH's. The pressure-falloff tests gave estimates of reservoir flow capacity (kh) ranging from 1,300 to 6,000 md•ft; similar in order to the results from the pressure-buildup tests mentioned above. This suggests that a large section of the rift zone has similar permeability to the area that is presently being developed. Therefore, provided that sufficiently high temperatures (650°F) can be encountered by development wells at reasonable depths, it is possible that wells will produce at least 2 to 3 MW per well.

The other two wells (KS-7 and 8) which encountered productive geothermal zones were drilled towards the southern edge of the KERZ. Both wells blew out: KS-7 in February 1991 and KS-8 in June 1991. The characteristics of these wells appear to be significantly different from the other deep wells, as they encountered high pressures and possibly high permeability at relatively shallow depths (KS-7 at 1,678 feet and KS-8 at 3,488 feet).

Downhole temperature surveys in KS-8 indicated temperatures of approximately 640°F at bottomhole. This, plus the high pressures, suggest that this well could discharge at a significantly higher flow rate than the other nearby wells. However, at the present time, the gas content of the fluid is unknown; therefore it is not possible to forecast its power output.

It does appear that well KS-8 has encountered higher permeability than the other deep wells. This therefore suggests that at

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some locations, it should be possible to drill wells of greater than 2 to 3 MW capacity in the future.

6.3 Estimation of Reserves

For the purposes of this resource assessment, the KERZ has been subdivided into three areas: the Developed Area; the Undeveloped Lower Rift; and the Upper Rift. This subdivision is based on differences among the three areas in the quantity and quality of data available for resource assessment. The location of the three areas is shown in figure 6.20, and the criteria for their subdivision are described below.

The Developed Area refers to the immediate vicinity of the HGP-A, KS-1, and -2, Lanipuna 1 and 6, and SOH-1 wells. The three-dimensional geometry of subsurface temperature distribution in this area is well known, because of (a) the relatively close spacing of the wells and (b) the availability of a large number of good-quality downhole temperature logs. The location of these wells, and the configuration of the 400°F isothermal surface, as defined by downhole temperature data, are shown on figure 6.21.

The Undeveloped Lower Rift Area refers to the section of the KERZ extending from well KMERZ A-1 eastward to the coast, but excluding the Developed Area. Four wells have been drilled in this area. From west to east these are: KMERZ A-1, SOH-4, Ashida 1 and SOH-2. The location of these wells is shown on figure 6.22. Although the wells are spaced apart from each other and from the wells of the Developed Area at distances ranging from 2 to 2.5 miles, their temperature profiles are similar, and consistent with their geological and topographical locations relative to the defined Rift margins. Temperature profiles for the four wells appear in Appendix A. In spite of their relatively

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wide separation, the subsurface-temperature distribution defined by these wells is reasonably certain, although less certain than the distribution defined by the closely spaced wells in the Developed Area. Figure 6.22 shows the configuration of as much of the 400°F isothermal surface as can be inferred from available data.

The Upper Rift Area refers to the section of the KERZ extending westward from well KMERZ A-1 to its western end at Kilauea Crater (figure 6.20). Although there are no wells drilled in this area to confirm subsurface-temperature distribution, there is good reason to believe, based on geologic analogy, that subsurface temperature distribution in the Upper Rift Area is similar to subsurface temperature distribution in the Lower Rift Area.

In recognition of the three different levels of data availability, the three areas have been treated separately for the purpose of reserves assessment. For each of the three areas, reserves values are estimated on the basis of the following relative certainties:

- Resources underlying the Developed Area are considered to be Proven, because a high level of certainty is provided by the data available from the closely spaced wells.

- Resources underlying the Undeveloped Lower Rift Area are considered to be Probable, although there are only a few, widely spaced wells, because they provide temperature and other data consistent with known geology.

- Resources underlying the Upper Rift Area are considered to be Possible, because there are no wells to confirm the subsurface

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temperature distribution inferred from arguments of geologic analogy.

Probabilistic estimates of reserves were made separately for each area.

Because the Puna resource is still in an early stage of development, the reserve estimation is based on a volumetric approach. We have used, with some modifications, the volumetric reserve estimation introduced by the U.S. Geological Survey. We have further improved this approach, to account for uncertainties in some parameters, by using a probabilistic basis.

In our method, the maximum sustainable net power plant capacity (E) is given by:

$$E = AhC_v(T-T_0)\cdot R/F/L, \qquad (6.1)$$

where
- A = areal extent of the reservoir,
- h = thickness of the reservoir,
- C_v = volumetric specific heat of the reservoir,
- T = average temperature of the reservoir,
- T_0 = base temperature
- R = overall recovery efficiency (the fraction of thermal energy in-place within the reservoir volume at a temperature of T_0 or more that is converted to net electrical energy at the power plant),
- F = power plant capacity factor (the fraction of time the 1 plant produces power on an annual basis), and
- L = power plant life.

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The parameter R can be determined as follows:

$$R = r \cdot e, \tag{6.2}$$

where r = recovery factor (the fraction of thermal energy in-place within the reservoir volume at a temperature of T_0 or more that is recoverable as thermal energy at the turbine inlet), and

e = thermal-to-electrical power (net) conversion efficiency.

The parameter C_v in (1) is given by:

$$C_v = \rho_r C_r (1-\phi) + \rho_f C_f \phi \tag{6.3}$$

where ρ_r = density of rock matrix,

C_r = specific heat of rock matrix,

ρ_f = density of reservoir fluid,

C_f = specific heat of reservoir fluid, and

ϕ = reservoir porosity.

PGV's modular power plant design indicates that when nine of the ten modules are operating, 53,300 lbs per hour of steam per module are required at 217 psia for a net power capacity of 2.827 MW. This is equivalent to an 'e' value of about 15.1%. This is an attractive value of 'e' for a small power plant module and compares favorably with conventional flash geothermal power plants.

The following parameters could be estimated for the Puna area without significant uncertainty:

$\rho_r C_r$ = 34.0 (based on representative rock types at Puna),

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T_0 = 350°F (minimum acceptable resource temperature),

F = 0.95 (PGV's assumption), and

L = 30 years (typical amortization period for a power plant).

The remaining parameters required for reserve estimation are considered to have significant uncertainty. Therefore, it is prudent to estimate reserves in a probabilistic way. We have applied a probabilistic approach using the Monte Carlo sampling technique, with the estimates of the uncertain parameters as follows.

For the Developed Area (Proven Resource), average minimum and maximum surface areas of 0.6 and 0.9 square miles were selected, based on the area enclosed by the 400°F isotherm at drilled depths. The location of this isotherm is clearly defined by the several wells drilled into it. At -3,000 feet msl, the area measures 0.8 by 0.7 miles, and at -6,000 feet msl it is 0.8 by 1.1 miles. On the north and south, the location of the reservoir boundary is controlled by the Rift boundaries. The east and west boundaries, on the other hand, are "information boundaries", controlled by the outer limits of drilling.

The minimum and maximum values of 6,000 and 7,000 feet were estimated for reservoir thickness, based on (a) the fact that the top of the reservoir, as defined by the 400°F isotherm, is at -3,000 feet msl and wellhead elevations are at +600 feet msl, and (b) the assumption that commercial wells can be drilled to a depth of 10,000 feet. A fixed, average value of 6,500 feet for thickness was used in the calculation.

Based on the temperature profiles from the several wells that have penetrated into the geothermal system, the average minimum and

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maximum temperatures for the Developed Area are estimated at 590° and 680°F, respectively. Minimum and maximum average recovery factors have been estimated at 5% and 15%, respectively, based on the range of recoveries typical of such geothermal systems.

The Undeveloped Lower Rift Area (Probable Resource) is 12 miles long. The minimum and maximum reservoir widths are estimated at 0.5 and 1.0 miles, respectively. These widths are based on analogy with the variation in reservoir width with depth in the Developed Area. These widths yield average minimum and maximum reservoir areas of 6 and 12 square miles.

The minimum and maximum values chosen for thickness are 5,000 and 7,500 feet, respectively, based on a reservoir top at -3,000 feet msl, 10,000-foot wells, and wellhead elevations ranging from sea level to 1,500 feet at well KMERZ A-1. A fixed, average value of 6,250 feet was used for thickness in the calculations.

The average minimum and maximum reservoir temperatures, projected from temperature profiles measured in well SOH-2 on the east and KMERZ A-1 on the west, were estimated at 630°F and 760°F. The maximum temperature used in the simulation, however, was reduced to the critical point of water (705°F), to reflect more realistically the possible subsurface reservoir conditions. Minimum and maximum average recovery factors have been estimated at 2.5% and 15%, respectively. While the upper limit of the recovery factor remained the same as for the Developed area, the lower limit was reduced to reflect a higher level of uncertainty in finding productive fractures in this area.

For the Upper Rift Area (Possible Resource), which is 20 miles long, the same range of reservoir widths has been used as for the Lower

Rift Area; that is, 0.5 and 1.0 miles. These values yield average minimum and maximum reservoir areas of 10 and 20 square miles. The minimum and maximum values of reservoir thickness are 3,000 and 5,000 feet, respectively, based on a reservoir top at a constant -3,000 feet msl, as in the Developed and Undeveloped Lower Rift areas, 10,000-foot wells, and wellhead elevations ranging from +4,000 feet at the west end of the Upper Rift to +1,500 feet at KMERZ A-1 at the east end. A fixed, average value of 4,000 feet was assumed for thickness in calculations.

The minimum and maximum average reservoir temperatures of 580°F and 630°F were inferred from the temperature profiles measured in well KMERZ A-1. Basing the estimate on only one well, located at the east end of the area, is justified: the tendency for temperatures to increase westward, toward the volcanically more-active end of the Rift, is counteracted by an increasing wellhead elevation to the west, while both the drilling depth and elevation of the reservoir top remain constant; this results in shallower penetration of the reservoir to the west.

Minimum and maximum average recovery factors have been estimated at 2.5% and 15%, as for the Undeveloped Lower Rift area, based on the same assumptions.

For porosity, a uniform probability distribution of 3% to 7% was assumed based on typical values encountered in fractured igneous rocks. Estimates of c_f and P_f are determined by the probability distribution of temperature.

The values of the uncertain parameters were sampled randomly repeatedly until a stable distribution was achieved, and the reserves

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were calculated for each sampled set of parameters. Finally, the statistical validity of the distribution was checked by various mathematical procedures to ensure a reliable distribution.

Figure 6.23 shows the histogram of the estimated reserves in megawatts for the Developed area. The results indicate that both the mean and the most-likely reserves value is 21 MW. Figure 6.24 present the results of Monte Carlo simulation for the Developed area in the form of a cumulative probability distribution. This figure shows that with a 90% level of certainty the reserves exceed 12 MW.

Figure 6.25 and 6.26 present similar results for the Undeveloped Lower Rift area. these figures show a reserves level of 48 to 581 MW, with a most-likely value of 141 MW. With a 90% level of certainty, the reserves are about 100 MW.

Figures 6.27 and 6.28 present similar results for the Upper Rift area. These figures show a reserves level of 40 to 468 MW with a most-likely value of 157 MW. With a 90% level of certainty, the reserves are about 82 MW. Another estimate of reserves by GeothermEx, using methodology relying primarily on slim hole data, provided results consistent with those of this report.

It should be noted that the above estimates refer to the reserves only. Unless commercially acceptable well productivity can be demonstrated in the Undeveloped Lower Rift and Upper Rift area, the reserves for these areas may not be economical to develop.

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7. DEVELOPMENT IMPACTS, RISKS AND MITIGATIONS

7.1 Well Drilling and Completion Characteristics and Problems

7.1.1 Casing and Cementing Operations

Wells KS-1 and -2 were drilled by Thermal Power during 1981 and 1982 to similar depths, and were completed using similar techniques and materials. Both wells were tested, and both developed similar problems during their early testing periods. Evidence of casing failure was noticed during the first flow test of each well. Further evidence of casing leaks was obtained when the wells were quenched and temperature and pressure surveys were conducted, revealing casing damage at depths from 900 to 940 and 1,040 to 1,080 feet in well KS-1, and from 1,093 to 1,987 feet in well KS-2.

The depths of the 13-3/8-inch intermediate casing shoes are 903 and 1,313 feet in wells KS-1 and KS-2, respectively. Both wells had losses of circulation below the 13-3/8-inch casing shoe; the cement bond between the 9-5/8-inch production-casing string and the formation may have been relatively poor because of the presence of these circulation-loss zones. Two other possibilities have been investigated regarding the casing failure. First, the grade and alloy of the casing may have been unsuitable for the chemistry of the geothermal fluids. Second, the buttress-threaded connections may not have been suitable for the magnitude of the thermal stresses that developed in these wells during production.

Workover of well KS-1 was conducted by squeezing cement into the damaged zone and cementing a new 7-inch casing string from the

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surface to 1,898 feet. The patch was placed with minor difficulties. During the same operation, the existing master valve was replaced by one with a higher pressure rating, to overcome the problem of the high shut-in wellhead pressures that developed during the early tests. The high wellhead pressure may have been a consequence of the accumulation of gas in the upper portion of the well. An attempt was also made to clean out the 7-inch slotted liner, without success, leaving a drilling tool (fish) stuck in the well at a depth of 4,570 feet.

In well KS-2, it was suspected that a four-foot gap had developed at the depth of the 9-5/8-inch casing tie-back (1,096 feet); this was later confirmed by a caliper log. A remedial program was conducted, consisting of squeezing cement into the damaged portion, and clearing wireline debris from the wellbore. This debris had been left in the hole during several logging operations, possibly because H_2S attack embrittled the stainless steel wireline so that it parted. Several cement plugs were squeezed into the damaged zone, without successfully plugging it. No further attempt was made to repair the damaged casing, and the wellbore cleanup operation was abandoned after experiencing severe difficulties in running the milling tools below 4,396 feet. A cement plug was emplaced at 3,175 feet, and the well was closed.

With the experience gained from the previous two wells, KS-1A was planned with a completely different design. The 20-inch casing was set at a greater depth of 1,377 feet, aiming to provide extra protection to the intermediate and production casing strings, by isolating them from the shallow lost-circulation zones. The 13-3/8-inch casing string was set at 2,701 feet, compared to 903 and 1,313 feet in KS-1 and -2.

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C-90 casing was used for the intermediate string; this type of casing is equipped with Vallourec VAM connections. Both the casing grade and the type of connection were important improvements, designed (a) to overcome the metallurgical problems seen in the previous wells, and (b) to provide the extra strength required in the casing joints in order to resist the thermal stresses imposed by the high temperatures.

The C-90 casing is manufactured from low-carbon, high-yield-strength steel, which provides a considerable resistance to corrosion and H_2S embrittlement. The 9-5/8-inch casing string was comprised of the same grade and thread. The 7-inch liner, consisting also of C-90 casing, was ordered with Hydril SFJ (super flush joint) threaded connections, which would permit future retrieval of the liner, should it become necessary to replace it with a new string.

Additionally, the 13-3/8-inch and the 9-5/8-inch strings were cemented by stages, using stage collars. The first stage was cemented, in order to anchor the casing; subsequently, a pre-tensioning force was applied to the rest of the casing. The force was maintained during the second-stage cementing operation and until the cement reached the required compressive strength to maintain the casing tension.

The wellhead equipment was specially designed to maintain the tension force in the casing, and to allow the thermal expansion of the casing during the well warm-up period. In this way, the well would be subjected to a significantly lesser degree of tension during the warm-up and production stages. In theory, the casing should return to the same state of stress as that which existed during pre-tensioning, if it is cooled down during quenching operations.

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This procedure, which had been used previously in certain wells in the Cerro Prieto field in Mexico, may have helped to protect the casing from exposure to excessive stresses during its initial warm-up and testing stages. However, it is highly unlikely that the casing could maintain the pre-stress condition homogeneously along its entire length indefinitely. Over time, there is a loss in the compressive strength of the cement, as a consequence of aging and exposure to sulfide-bearing aquifers. If this is the case, the pre-stressing technique may only delay the problem for several years, until the cement becomes too weak to maintain a strong bond between the formation and the casing.

Well KS-1A may have been slightly favored by the extra protection provided by the deeper setting of the 20-inch and 13-3/8-inch casings, which isolate the 9-5/8-inch production-casing string from exposure to the more-reactive aquifers. After its completion, well KS-1A was tested extensively, without immediately experiencing the problems that were observed in the KS-1 and -2 wells. However, the well was worked over in March-April 1991 to drill out a plug, and attempt to clean out, deepen and improve the well's injectivity. A succession of problems occurred during the workover; parted and corroded casings (9-5/8-inch below the pack-off in the casing head and at 2,910 feet depth) were discovered, a leak in the drill string occurred, bridging occurred (at 5,636 feet depth), and finally 311 feet of drill string were left in the hole below 5,745 feet. Afterwards injection tests pumped in excess of 200 gpm down the hole. No consensus was reached at that time on further rework attempts.

The mechanical problems of previously drilled wells (and the solutions found for these problems) provide a useful history for use by operators in designing future wells, and in regulatory review by the

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State. State regulatory agencies should make use of the well histories during permitting procedures.

7.1.2 Core-Drilling Operations (SOH Programs)

Because of environmental considerations, and because of regulatory constraints imposed by permitting agencies, the original SOH drilling program was modified significantly. This involved changes to the type and capacity of the drilling rig to be contracted, as well as to the hole design. Diameters of wells, casing programs and well-control equipment were redesigned to accommodate the statutory regulations and the constraints imposed after mediation sessions held on the Island of Hawaii between the SOH project management and concerned parties.

By the conclusion of the third SOH well, large cost-overruns had been incurred, especially during upper-hole coring and hole-enlargement operations. The SOH program had as its objective the continuous coring from surface to total depth, and the fulfillment of this primary objective, together with the requirement to install adequate casing in the upper portions of the well for the protection of the shallow aquifers, led to the use of hole openers. Because a coring rig cannot perform a one-pass drilling of adequate diameter for casing, this hole-opening operation was slow and inefficient, imposing severe cost and time penalties on the program.

The specialized nature of coring operations results in the design of drilling rigs that have a limited capability to perform rotary work in the upper portions of the hole, where large-diameter tools normally are used. Further, the limited size permitted for the drilling pads resulted in the contracting of a relatively small drilling rig.

The resulting daily cost for the coring rig was nearly the same as for a larger and more-powerful rotary drilling rig suitable for drilling holes of up to 16-1/2-inch diameter.

The contracted rig did achieve acceptable rates of penetration during the primary coring operations. However, the subsequent operation of opening the hole from the core size to a diameter sufficient for running casing was time-consuming and costly. It had to be done with full circulation of fluid to the surface, in order to avoid twisting off the small-diameter, thin-walled core-drilling string under the excessive torque imposed by the accumulation of rock chips. This situation required repeated remedial cementing operations in the intensely fractured basalts to cure lost circulation. It further slowed the progress of the operations.

Future wells planned by the State should be drilled with a simpler, clearer, less-complicated objective, aiming exclusively either (a) to perform safe testing and assessment of the geothermal reservoir, or (b) to obtain core samples of the formation. The first alternative is preferable. The information obtained by the rotary drilling method, involving the drilling of larger-diameter holes, provides more information for the investigation and assessment of the geothermal reservoirs than does core drilling. Rotary cuttings provide very useful stratigraphic and mineralogic information, if not as simplistic structural information. Every effort should be made to obtain permits to drill and flow test future SOH wells, and to design appropriate rotary-drilled medium-diameter exploratory wells.

Core samples may provide materials for various academic laboratory research projects, but not definitive information about geothermal resources. Such studies as fluid inclusion analyses may show

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relict temperatures and compositions but not necessarily present conditions of the geothermal reservoir.

Chapter 7.1.3 offers specific guidelines for the design and drilling of a medium-size-diameter (5-7/8-inch production diameter) exploratory well, to be drilled with a rotary rig, having the capability of safely producing reservoir fluids and admitting adequate downhole instrumentation for measurement and monitoring of reservoir parameters. Such exploratory wells can be designed as directional holes, thereby allowing the exploration of multiple or inaccessible targets from single drilling pads. The mud motors, bits and drilling assemblies of adequate size for use in directional drilling are not available for cored holes.

7.1.3 Design Guidelines for Medium-Diameter Exploratory Wells

Medium-diameter exploratory wells are suggested because they combine the possibility of reaching and testing the deep reservoir targets to at least 7,000 feet, with minimum cost and risk. Drilling of such wells will require a rotary rig, of larger capacity than the coring rig used for the SOH holes. Therefore, larger drilling pads (about 1 acre) will be required.

Every permitted drilling pad must have a working area and waste pits of an adequate size and volume for the necessary well-testing operations; every pad must be able to accommodate several directional wells.

Medium-diameter exploration wells are designed following the same criteria used for production wells, with the same standards for materials, equipment, drilling practices and operational safety. Medium-diameter wells successfully drilled into permeable parts of the geothermal reservoir would have a restricted production capability. If converted for commercial production, they would probably be limited to a few megawatts.

Design and cost guidelines for a generic medium-diameter well are given in tables 7.1 and 7.2, and in figure 7-1. The following design is recommended, based on the cumulative experience of drilling the Lanipuna, KS and SOH wells in the KERZ.

- The shallowest part of the KERZ (to about 1,000 feet) consists of highly fractured basalt flows, where the curing of losses of circulation is cumbersome and costly. The recommended well design calls for the installation of 30 feet of 20-inch conductor pipe, below which drilling shall proceed using a light mud to clean the hole. Every attempt shall be made to plug or minimize circulation losses, using cement plugs and massive amounts of lost-circulation material (locally available materials such as bagasse, macadamia shells and coconut fiber should be kept on location). Experience has shown that some of the fractures are of such magnitude that most of the drilling cuttings are lost into the fractures, and that drilling with total loss does not represent a risk of trapping the drillstring.

- Cementing of the 13-3/8-inch casing at about 1,000 feet should be done with the use of a hydraulically operated stage-cementing collar. Halliburton manufactures this type of cementing collar, known as the HOS cementer. The collar should be positioned a few hundred feet above the largest lost-circulation zone in the well and the first-stage cement volume should be calculated with a 100% excess, in order to begin healing the loss zone. After the first stage has been pumped, a short time period will be allowed before opening the ports in the stage-cementing collar. Once the collar is open, the upper portion of the hole will be circulated. The cement volume for the second stage can be pumped 6 to 12 hours later. Once cement reaches the surface, provisions must be made to follow the cement top each hour (if it drops in elevation inside of the annulus), with cement pumped from the surface. It is likely that successive top cementing jobs will also be necessary to fill the annulus.

- Drilling of the 12-1/4-inch and 8-1/2-inch holes to about 2,000 and 4,000 feet respectively should be less difficult with respect to losses of circulation. Each well represents a different set of formation conditions between 1,000 and 4,000 feet; but wells drilled from the same pad will be able to rely on history of prior wells for anticipated formation conditions. Some areas in the vicinity of the KS wells and SOH-1 show a pervasively fractured formation at depths varying between 3,900 and 4,400 feet.

  Depending upon location, the problems of losses of circulation and caving-in of the 12-1/4-inch hole may vary from very minimal to very massive. Therefore, in the cases where drilling proceeds smoothly through these depths, the 9-5/8-inch casing can optionally be extended to a depth of as much as 4,000 feet. This procedure allows the possibility of cementing an intermediate casing of 7-inch diameter to cover any other broken zones encountered below this depth, or in the best of the cases, to avoid the expense of running and cementing the 7-inch casing.

- The design and practice of cementing the casings must follow the highest standards for this type of operation in geothermal wells. It is recommended that an experienced cementing contractor be in charge of this operation under the direction of the drilling engineer, and that the contractor furnish all necessary storage facilities for the cement and additives, the pumps and ancillary equipment, plus the personnel to perform the work.

  The cement should be of class "G", blended with silica flour and additives per the recommendations of the cement company laboratory, which will design the slurry according to the downhole chemical and physical conditions. Conditions may be expected to vary from pad to pad.

- The temperature distribution at depth also varies widely, depending on location. Temperature conditions determine the depths at which mud motors can be used for directional drilling. In the area of the KS and SOH-1 wells, temperature gradients are relatively low to a depth of 4,000 feet. Below this depth, temperature gradients increase rapidly, potentially limiting the use of mud motors. Therefore, directional drilling using mud motors in this area, where the directional kick-off point is located between 1,500 and 2,000 feet in depth, will be limited (a) to the building of the desired angle and bearing between the depth of the kick-off point and 4,000 feet, where the 7-5/8-inch casing would be cemented, and (b) to control the angle with a packed assembly below the depth of the 7-5/8-inch-casing shoe.

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- Because the success of directional drilling depends greatly upon the temperature of the fluid circulating in the hole, it is recommended that a large mud-circulating system, including a mud-cooling tower, be available for use with the rig, to lower the mud temperature to a range where the motors and the steering tools can be operated safely.

- Mud motors and steering tools are manufactured in an assortment of diameters and working temperature ranges. However, most of the slimmer hole tools are manufactured for working in lower-temperature environments. Therefore, a well design with shallow kick-off points and larger-diameter mud motors would be favorable for the operation.

- The thermal stresses and corrosive environment to which the casing strings are subjected have to be overcome by the metallurgy of the casing, the wall thickness and the type of connection that is chosen. L-80 or C-90 casing, with VAM-type (or similar) premium connections, are recommended.

- The 5-7/8-inch-diameter section of the well is normally the most critical, because of its high temperature. However, because of the reduced diameter of this section, the penetration rates in this section should be higher than was experienced in the larger-diameter KS wells, and more likely will be similar to that of the Lanipuna and SOH wells. Losses of circulation should be allowed during this stage. Therefore, drilling can proceed with water or with very light mud, without mud returns to the surface. Under such circumstances, the driller should flush the cuttings away from the bit, by circulating slugs of dense mud or polymer at every connection.

If excess dragging or torque are detected, a polymer-based mud system would have to be designed and used.

- Upon reaching the final depth, a 4-1/2-inch slotted liner should be run in the hole to protect it from being obstructed by broken formations. The slots of the liner should be machined at a factory and should conform to the standards normally used in the geothermal industry. A minimum inlet area of 18 square inches per linear foot of pipe (based on 2-1/2 by 1/4-inch slots) is recommended.

- It is also recommended that the slotted-liner connections be of the Hydril SFJ-type, with no external upset in the couplings. This type of connection allows an increase in diameter of the liner, with respect to hole size, an improvement in the strength of the connection, and a reduction of the friction of the pipe as it is lowered into the open hole.

7.2 Impacts Arising from Fluid Chemistry

The fluid chemistry of wells in the KERZ will have an impact on the pace and style of geothermal resource development. Possible changes in fluid composition over time may affect well operations and the power-production cycle. Attention must be given now to these questions, in order to avoid risks to health and safety, and to ensure economical project development. The impacts and risks discussed below are: possible long-term changes in fluid chemistry; disposal of non-condensible gases; corrosion control; scale control; possible contamination resulting from fluid injection; and monitoring of mitigation and abatement practises.

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7.2.1 Possible Changes in Fluid Chemistry

It should not be assumed that the fluid chemistry at any single well or set of wells will remain constant over time, particularly under the stress of long-term production. Experience at well HPG-A points this out, as do the production histories at other geothermal fields worldwide.

Well HGP-A first produced a fluid characteristic of meteoric water altered by residence in hot volcanic rocks. Over time, this fluid progressively shifted in chemical composition to higher Cl, together with higher total dissolved solids (TDS), as the well tapped an increasing fraction of thermally altered seawater. During the chemical shift, the level of dissolved SiO_2 remained constant, whereas the ratio Na/K increased. SiO_2 adjusts to changes in aquifer temperature more rapidly than does Na/K, and the observed pattern suggests that the source of altered seawater is cooler than the near-well environment. Even if the cooler seawater component was heated by rocks near the well, the chemical shift suggests that cooling eventually might take place.

The potential for changes of fluid chemistry at other wells is increased by evidence of strong vertical heterogeneities in aquifer characteristics. Well HGP-A apparently produced from an upper liquid-dominated zone, and a deeper steam zone. Other wells in the area show evidence of steam production from deeper levels. Therefore, depending upon how deep a well is drilled, how it is cased, and the pressure depletion of its different zones, its composition may differ from that of its neighbors, and may change over time.

In geothermal systems which produce a high fraction of steam from the reservoir, it is common to see the steam fraction increase over time. This means that the enthalpy of the wellflow increases, and its productive capacity may increase, even if the total mass flow rate decreases. Power plant design must take into account this possibility, along with the possibility of declining pressure.

Cases of 2-phase wells cooling over time are relatively rare, except at wells which are impacted by injection into another well nearby.

7.2.2 Non-Condensible Gases

As described in Chapter 5.2, data concerning NCG in the Puna reservoir are very limited. Concentrations of gases in steam at about 155 psig from wells HGP-A and KS-1A have been about 2,200 parts per million (ppm-wt). This includes 900 to 1,200 ppm-wt H_2S, which is very high, but not unheard-of relative to worldwide experience: some wells at The Geysers and Coso reservoirs in California have produced similar H_2S concentrations. Since the steam fraction of the total flow has not been recorded, the concentration of gases in the steam cannot be corrected to provide total flow values.

H_2S does present a significant corrosion potential, and it requires that the condenser and injection system be well-sealed and maintained at positive pressure at all times, in order to avoid intrusion of oxygen from the atmosphere.

Drilling experience in the area (KS-7 and -8, for example) has encountered concentrated, high-pressure gases trapped above or near the top of the reservoir. There is no indication that these high concentrations extend down into main production zones.

Changes in the gas concentration over long-term production cannot reliably be predicted. Experience in other geothermal fields has been that NCG tend to remain quite stable as long as a well continues to tap single-phase liquid-dominated production zone(s), and as long as the well is not affected by injection of gases into other wells near-by. When two-phase-reservoir conditions develop, gas concentrations in well flow tend to rise while the fraction of reservoir steam in total flow increases (often for many years). Gas concentrations fall when the deep, boiling, source fluid becomes depleted. Because the Puna wells tend to produce high steam fractions initially, the long-term trend is likely to be gases decreasing from the initial level. However, this cannot be guaranteed.

The long-term production of gases at the PGV venture may be affected by the intended injection of all gases back into the reservoir, along with all of the produced water and steam. As long as pressures in the injection wells are high enough, the gases will be re-dissolved in the injected water. This can be confirmed by using the amounts of gas and water injected, and the temperature of the injection stream, to calculate the gas solubility and then compare it with injection pressure.

If gas solubility is exceeded, there is some potential for a gas breakthrough to production wells. Breakthrough would not cause a direct problem, unless it causes an increase of gas concentration beyond the capacity of the power plant. This risk is relatively remote.

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A related, but seemingly remote possibility is gas breakout from injection wells into shallow aquifers. There is no way to predict whether this would be detected at any of the wells intercepting shallow aquifers. Probably there already occurs a certain amount of gas discharge from the hydrothermal system and from magma cooling deep beneath the KERZ, but presumably this is masked by the high rate of recharge of meteoric water within the KERZ.

7.2.3 Corrosion

The potential for corrosion of well casings and surface lines may come principally from sulfide stress-cracking along interior surfaces. When the HGP-A production system was overhauled in August 1983, there was relatively little evidence of corrosion in air-free parts of the brine system. In the steam-supply system there was some iron sulfide and iron oxides (products of corrosion) where air had intruded, in thicknesses about 0.04 inches and less, and only at certain locations.

The corrosivity of fluids produced at other wells in the area is not well-documented. Corrosion is said to have been a problem during the drilling and testing of the earlier KS-series holes; this may have in part been a function of oxygen carried by the drilling fluids interacting with reservoir H_2S. However, some fluid samples taken from well HGP-A in 1977 and 1978 reportedly had pH's between 2 and 3; fluid pH as low as 3.8 developed during testing of KS-1A; and a pH of 3.6 has been reported from KS-3.

There are geothermal wells in other fields that produce fluid at a pH about 3.5 without problems, but pH levels this low always advise caution. Well fluid pH's and iron concentrations should always be monitored, and in some cases the wall thickness of wellheads and flowlines may have to be tested on a regular basis, along with other corrosion monitoring.

In this regard, the general character of the KERZ system presents some potential for a long-term increase in steam corrosivity. If the system draws an increasing fraction of seawater, there will occur a long-term increase in Cl and a lowering of reservoir pH. These changes should not of themselves be a problem, unless the reservoir dries out significantly with time, and begins to produce superheated steam. This superheated steam could carry volatilized hydrochloric acid, which can form extremely corrosive, low-pH, high-Cl condensate films. Mitigation of the acid by injecting caustic into the steam flow could become necessary. This risk is relatively remote, and speculative; mitigation is simple, although with an added cost.

There presently is evidence of boiling at the top of the thermal system near sea level, some 600 feet below the land surface. If the environment near sea level is receiving large amounts of H_2S rising from depth, and if this is mixing with oxygenated meteoric water percolating from above, there then would develop a strong potential for acid groundwaters. These could cause severe external casing corrosion at the water-table surface. Well-casing design should take into account the impact of this hypothetical corrosion, as the optimum mitigation.

7.2.4 Scaling

The potential for SiO_2 scaling is illustrated on figure 7.2 which shows that the typical reservoir liquid produced from well KS-1A

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will become oversaturated with 230 ppm-wt SiO_2 at a steam-separation pressure of 217 psia. The reservoir liquid is believed to carry about 780 ppm SiO_2 at 625°F, based on the solubility of quartz in a 2.84 weight-percent (wt%) NaCl solution. This is a probable upper limit for reservoir SiO_2, because the actual reservoir salinity probably is closer to 2.0 wt%, and measured SiO_2 data suggest that the reservoir-liquid production comes from a zone between 575°F and 625°F in temperature (see discussion of SiO_2 temperatures in Chapter 5.2).

In preparing figure 7.2 it was assumed that conductive heat losses are minimal, and the effects of brine pH and co-precipitation of iron and aluminum are ignored. Brine pH has two opposing effects. An increase of pH causes silica solubility to increase, therefore depressing the tendency of an oversaturated solution to form scale. Simultaneously, an increase of pH tends to increase the rates of chemical reactions which lead to scale formation. Aluminum and iron in solution also tend to promote scale formation, by reacting with silica. For the level of detail considered herein, these various effects should be considered insignificant.

The re-mixed brine and steam condensate should be oversaturated with amorphous SiO_2 by about 30 ppm-wt upon leaving the power plant, assuming that there is no conductive heat loss from the brine, and that the condensate has a temperature of 212°F, and an enthalpy of 180 British thermal units per pound (Btu/lb). If this mixture also includes the non-condensible gases, the CO_2 and H_2S being injected will tend to lower the pH, depressing the scaling rate.

These conditions can be compared with the composition of water from HGP-A upon leaving the separator, reportedly containing 800 to 850

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ppm-wt SiO_2 at about 170 psia during the seven years of production from 1982 to 1989 (Thomas, 1987; Thomas and Bell, 1988). This range is shown as a short line on figure 7.2. Reservoir SiO_2 concentration was lower at HGP-A than is anticipated at the PGV project, because the HGP-A reservoir was somewhat cooler, with temperatures averaging 560° to 565°F. The range 800 to 850 ppm-wt SiO_2 in the separator water was consistent with boiling at the measured reservoir temperature; therefore, it is not expected that more than a few ppm-wt SiO_2 could have been lost during scale formation, before water samples were collected.

As shown by figure 7.2, the HGP-A water was approximately saturated with amorphous SiO_2 at steam-separation conditions. SiO_2 scaling occurred in the production separator and flow lines, but the amount of scaling in the production system was not prohibitive. The brine-handling system was inspected in August 1983 after about 22 months of production. The 10-inch diameter pipeline between the wellhead and primary separator contained a layer of vitreous SiO_2 scale, about 0.02 inches thick. The primary brine separator (4′7" diameter; 17′10" high) was coated with SiO_2 with <5% iron sulfides (corrosion products), about 0.1 inch to almost an inch in thickness. In the outlet pipe, downstream of the separator, there was 0.2 to 0.8 inches of scale. However, there was evidence that scaling in the outlet pipe had been enhanced by flashing in the pipe immediately downstream of the separator. It also was found that small-diameter nipples and connection points, such as sample points, had been bridged by scale, probably because of heat loss or turbulence.

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The HGP-A system received its third overhaul in November 1987, when SiO_2 scale about 0.3 thick was found in the flash separator, and deposits 0.25 thick were found in the two existing 4-inch and 3-inch diameter flow lines leading to the brine-disposal basin. The scale in the separator was removed mechanically; the brine lines were replaced.

Based on this, and assuming the conditions shown on figure 7.2, it is expected that the PGV water will form scale in the production flash separator (and possibly upstream of the separator) at a rate higher than that observed at well HGP-A. Reservoir temperatures exceeding 600°F also are expected to contribute to wellbore scale formation, with the likely appearance of sulfide scale in addition to SiO_2. It is not possible to quantify the expected rate, because the factors which affect rate are complex and the exact fluid composition and reservoir temperature are unknown. Reservoir boiling probably will cause reservoir SiO_2 scaling; this may in turn locally reduce reservoir permeability. The loss probably will not be significant.

At lower temperatures in the HGP-A production system, downstream of the flash separator, there was an additional problem with silica: abundant flocculated silica sealed the percolation ponds and required that they be greatly enlarged. The discharge conditions from the proposed PGV plant will be different, because the brine will be mixed with steam condensate and injected back into the reservoir. As shown on figure 7.2, this mixing will reduce the SiO_2 oversaturation from about 230 ppm-wt in the production separator to about 30 ppm-wt oversaturation at the mixing point. This is a low level of SiO_2 oversaturation and scaling should be suppressed by gas injection. It indicates that further downstream scaling probably will be nearly insignificant, unless the fluid is allowed to cool substantially. If the injection well is much cooler than the fluid temperature at the mixing point (about 300°F), there will be an increased risk of scaling in the injection well, with a resulting loss of injectivity.

7.2.5 Contamination Resulting from Fluid Injection

There is a small possibility that injection of water and gases into the KERZ reservoir will cause contamination of shallow ground-water, if the injection is not confined to the intended deep zones. There is presently no way to evaluate firmly the possibility of this occurring, but the potential can be said to exist because there already is at least minor outflow from the thermal system. The potential for contamination will increase as injection pressure increases; however, because injection pressures are not yet determined fully, the point is moot. Any contamination which occurs may tend to flow to the south and east, in the direction of the pre-existing ground-water gradient. In such a case, the impact on existing wells used for ground-water production may be insignificant, because wells to the south and east already are hot and saline. Further evaluation of this matter must await better definition of the ground-water system in the area.

7.2.6 Monitoring of Mitigation and Abatement

The degree of need for mitigation of these development impacts will depend upon the design and extent of field development, and the chemistry of the produced fluids. To the extent that fluids produced from the geothermal system are successfully injected back into the reservoir, there may be no chemical impacts to mitigate. However, there may occur some releases of fluids to the surface environment during well testing, and there always is a risk of unintended well discharges, such as occurred at well KS-8 in 1991. Possible contamination of ground-water as the result of geothermal development can be determined and monitored by regular, periodic sampling of ground-water wells in the area. It is understood that this already is being done.

The management of fluid releases can be designed to include the abatement of H_2S by chemical removal from the process stream. Similarly, waters produced during testing can be either discharged to the surface, allowed to percolate, or injected back into the reservoir or into shallower aquifers, according to the decisions taken by the project management in conjunction with the appropriate government authorities. Monitoring of releases can include measurements of ambient H_2S on a periodic or continuous basis. However, these measurements should be designed to take into consideration the presence of natural releases of H_2S and other gases from nearby volcanic activity.

7.3 Natural Phenomena, Risk and Mitigation

The KERZ is a tectonically and volcanically active area extending eastward from Kilauea Caldera, an active shield volcano near the south coast of Hawaii. Young rift zones on Hawaii, extending from the principal volcanoes, are active seismically and form the locus of eruptions of lava flows. Earthquakes accompany the filling of the principal volcanic center with new magma from depth. Magma then may move laterally into the rifts; in the case of Kilauea, southward and eastward into the KERZ, or southwestward into the KSWRZ, a comparable rift feature on the other side of Kilauea. The rift zone widens as it undergoes intrusion, and additional earthquakes mark the vertical movement of magma into dikes. Eruptions may follow, through fissures along the rift, and from cones.

7.3.1 Volcanic Eruptions

Flows of lava from a few feet to tens of feet in thickness are erupted from the cones and fissures, and normally flow toward the coast. Eruptions frequently develop a lava-tube system; lava flows downslope through the tubes and emerges at the coast. The lava moves at varying velocities, although often as a viscous mass with a blocky front. Such events have occurred repeatedly during the last century all along the Puña Coast; more than 10% of the land surface is comprised of flows less than 100 years old. A particularly active eruptive period occurred in 1955 near Opihikao in the KERZ. Subsequently, flows have occurred in the lower KERZ in 1960, and in the KMERZ about 10 miles westward from Pahoa in 1963. A flow in the KMERZ overwhelmed a prospective True Geothermal drilling location in 1989.

Typical of the eruption events is that of 1959-1960, when tiltmeters near the summit of Kilauea Iki showed that the volcano was bulging upward and outward. Seismic events followed, and eruptions began near the principal crater, lasting several months. A few weeks later, seismic activity began 25 miles southeast of Kilauea Iki along the KERZ. Fissures developed and lava erupted from vents extending nearly one-half mile along the rift, and reached the ocean near Kapoho. Steam, ash and pumice were erupted as well as lava.

Historically, volcanic activity has been uniformly distributed along the entire length of the KERZ. However, during the past 30 years, activity has been concentrated in the upper and lower KERZ. Since January 1983, activity has centered on the Puu Oo vent in the upper KERZ; flows have moved downhill and have destroyed the town of Kalapana as well as many homes in subdivisions below the vent. These latest events have not been from fountains distributed along wide areas of the

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rift, but instead from a point source. This current phase of activity is one of the longest historic eruptive series.

There is therefore a definite risk that a geothermal wellfield and power plant could be damaged or destroyed by flows of lava and/or by the eruption of a cinder cone. However, given the factors of (a) uncertain periodicity of volcanic eruptions, their extent and intensity, and (b) the great length of the KERZ (including its offshore segment) along which eruptions can occur, plus (c) the local control exerted by topography on flow direction, and by micro-climate on conditions of ash and cinder fall, it becomes impossible to predict whether a specific site will be free of damage, or lightly coated by ash or bombs, or buried by lava flows during the economic lifetime of a geothermal field development.

The new PGV power plant is located near the 1955 fissure eruptions; this is not itself an indication of future eruption risk to the plant, since new along-rift lava fountains generally make new fissures.

Probabilities of risk or damage can be estimated, based on history, topography, and assumptions regarding magma-generation rates, and rates of rift expansion and dike intrusion into the KERZ. However, these can be no better than any probabilistic forecast.

Once a decision is taken to develop a geothermal wellfield or power plant, certain actions can be taken to mitigate somewhat the possible effects of volcanic eruptions. First, sites for power plants and other surface facilities can be chosen with an eye to topography, to avoid the most obvious courses for lava to flow and pond, and to locate

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in the shelter of physical features to minimize the impact of cinder falls and lava bombs.

Second, the sites can be protected by earthen dikes, stone or concrete walls, and ditches, to impound or deflect the course of lava. Roofs can be designed to shed rather than accumulate ash and cinders, and to withstand aerial bombardment by rocks. Windows, likewise, can be screened or barred. Walkways can be covered.

Third, the continuous monitoring of seismic events and the measurement of inflation of Kilauea Volcano by the U.S. Geological Survey permits a 48-hour or greater warning forecast of potential eruptions along the KERZ. Lava movement often is slow. These factors provide sufficient lead time to permit properly designed wellhead equipment to be installed within a vault, to be protected against eruptions. The first few inches at the bottom of a lava flow chills almost immediately, to form a basal crust which thereafter insulates against downward heat flow, protecting wellhead facilities.

Some equipment may be left mounted on skids, or constructed for simple dismantling, so that it can be removed on short notice by tractor. Other equipment may be installed or stored outside of the KERZ, connected only by computer, telephone line or electric cable to the main power plant and wellheads. This might include most of the power plant control systems.

Fourth, a system for monitoring microearthquakes might be installed at or near the geothermal facility, to provide the site-specific detection of volcanic seisms. The timely identification of volcanic seisms, becoming shallower and approaching the geothermal site with time, might allow for quicker, safer evacuation of personnel, shut-down of the power plant, and removal of modular or skid-mounted equipment.

Fifth, detailed procedural manuals should be prepared, giving instructions for standby, shut-down, and evacuation; training exercises and drills should be instituted.

Finally, none of this may be necessary: wells drilled in the KERZ have remained open and undamaged for more than 15 years. As understanding of the magmatic processes beneath the KERZ improves, it may be possible to develop a truly predictive suite of siting and forecasting criteria and truly protective mechanisms.

7.3.2 Seismic Activity

The KERZ is continuously active seismically. However, the overwhelming majority of earthquakes are below the threshold of recognition by humans, and most of the remainder have little potential to cause damage.

Several kinds of seismic events occur along the rift. Some earthquakes, with shallow focus and episodic frequency, are directly related to volcanism, and represent extension of the rift zone, as magma is forced into fractures. Other earthquakes, with deeper focus (about 10 km), represent tectonic movement along major faults, as the part of the island south of the rift zone slips southward and downward. A third set of seismic events indicates that minor movements and fracturing are occurring on small faults within and adjacent to the rift zone, as an adjustment of the rocks to the major extension and slippage. The most frequent seismic activity is related to volcanism and is generally of lower magnitude than tectonic activity. This infers that individual events are of short duration, with relatively low acceleration and small displacement, and may cause only minor damage to properly engineered geothermal facilities.

It has been observed by geophysicists and geologists at the HVO (oral communications, 1979) that there may be a structural and lithological boundary about 7 miles west of HGP-A, which may tend to restrict the occurrence of volcanic earthquakes. In that case, the middle and lower KERZ may experience fewer volcanism-induced earthquakes. However, that part of the rift was apparently spread in 1975 and 1977 as a prelude to the volcanic eruptions of the 1980s and 1990s; it is not clear whether the rifting and eruptions were accompanied by intense swarms of volcanic earthquakes.

There is seismic risk associated with movement along the Hilina fault system, southward of the rift zones. Movement along this fault resulted in the Kalapana earthquake of 1975 (magnitude 7.2). There has been relatively little structural damage as the result of historic earthquakes, and ground accelerations rarely exceeded 0.4g, despite the relatively large magnitudes of the some earthquakes (ERCE, 1990).

The most significant tectonic earthquakes recorded on the Island of Hawaii are listed in table 7.3. Thus, seismic activity remains a risk factor, although probably far less serious than the risk associated with volcanic eruption.

As the understanding of magmatic and structural processes beneath the KERZ improves, it may be possible to forecast the probable recurrence interval of the maximum magnitude earthquake and maximum ground acceleration to be expected at each geothermal development.

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These parameters would be built into the design and layout specifications.

To mitigate against this poorly defined but probably minor risk today, structures should be built in accordance with the seismic safety criteria of the pertinent Hawaiian construction codes, and should be designed to withstand the maximum-recorded ground acceleration in the Island of Hawaii. Manuals should be prepared for rapid, safe shut-down and evacuation, and training sessions and drills should be held periodically.

Installation of a network of seismographs might be useful at each developed geothermal field. Records of earthquakes should be analyzed, to determine their spatial, depth and temporal pattern. From this, site-specific forecasts of seismic risk may be developed.

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8. NUMERICAL MODELING OF THE RESERVOIR

8.1 Introduction

Geothermal systems evolve over geologic time, with the thermodynamic and hydrodynamic conditions in the system attaining a dynamic equilibrium. The rate of change in the natural system is exceedingly small relative to the changes that would be induced by exploitation; hence, for all practical purposes, undeveloped geothermal systems are considered to be in a quasisteady state. Numerical modeling of this initial (or natural) state has the following utilities:

- verification of the conceptual hydrogeologic model;
- formation of a quantitative basis for considering future development scenarios;
- improved accuracy in reserve estimation; and
- improved planning of development of the system for exploitation.

Quantitative modeling of the natural state must be based on a conceptual model that is, in turn, based upon many sources of information (geological, hydrological, geophysical, geochemical and reservoir engineering data). By quantification of its various aspects, a model can be tested and refined, or even discarded in favor of a more realistic one. A successful model will match quantitatively and/or qualitatively a wide range of observations about the system. The process of developing such a model also provides insight into important

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system characteristics, such as formation permeability, boundary conditions for fluid and heat flow and the thermodynamic state of fluids throughout the system. Even if an unambiguous or accurate quantification of these parameters cannot be fully achieved, it may be possible to redefine the constraints on the various parameters that are used for estimating reserves and the reservoir response to exploitation.

It is necessary to have a good conceptual model of the geothermal system on which to base the mathematical model. For the Puna development area, a conceptual model which integrates the results of the drilling and testing results from the new wells will have to be developed after PGV's drilling program is completed.

8.2 Initial State Modeling Procedure

Figure 8.1 summarizes the procedure followed in the first stage of initial state modeling. As mentioned above, the process begins with the definition of the conceptual hydrogeologic model. After careful consideration of the conceptual model, a grid will be generated to discretize the geothermal system in three dimensions. The grid will be delineated on the basis of the following constraints:

- the need to define an individual grid block for inferred or known zones of fluid discharge and recharge;
- topography;
- the location of structures or aquifers that are believed to control fluid or heat flow;

- lithologic changes that are considered to cause significant variations in hydrologic properties (porosity, permeability, etc.) or thermal properties (thermal conductivity, specific heat, etc.), and;

- the density of grid blocks in relation to the amount of available information.

In setting up the grid layout, the physical parameters associated with each block, such as block volume, area of contact and the distances between the grid block node and all adjoining nodes, will be determined. In addition, it will be necessary to define the rock and fluid properties associated with each grid block based on observed or inferred data. If no observed or inferred data are available, the parameter(s) will be defined based on knowledge of similar systems. The parameters to be quantified include:

1. porosity;
2. permeability in the horizontal (x and y) and vertical (z) directions;
3. density and compressibility of the rock matrix;
4. thermal conductivity and specific heat of the rock matrix;
5. water/steam relative permeability characteristics;
6. water/steam capillary pressure characteristics (capillary pressure is assumed to be zero in this case);
7. temperature;
8. pressure;
9. steam saturation (or enthalpy); and
10. gas content (if required).

The main goals at this stage of initial state modeling are to match the subsurface temperature and pressure distributions and to verify the location and extent of the heat/mass recharge and discharge aspects of the conceptual model. In this context, the major variable used is rock permeability. Thermal conductivity may also be important in areas where conductive heat transfer predominates. However, in general, thermal conductivity is set at an average value. Storage properties such as porosity, rock density and rock specific heat do not have a significant impact on initial state modeling. Therefore, it generally suffices to use average values for these properties at this stage.

Relative permeability functions provide a method of controlling the relative flow of steam and water between grid blocks; as such, they are very important variables in the simulation of two phase geothermal systems. The functions are generally defined in terms of water saturation (or volume fraction) and describe how the permeability of the rock to one phase (for example steam) is affected by the presence of a second phase (in this case water). In geothermal systems, the form of the functions are not well known and it has been a widespread practice in the past to use functions borrowed from the petroleum literature, such as the Corey relative permeability functions.

To improve the basis for the definition of the relative permeability functions in geothermal simulation studies, production data from a number of fields where two-phase conditions occur have been analyzed. Data from the Wairakei geothermal field in New Zealand have been analyzed in this way and the functions to be used in the Puna model will be based, in part, on this analysis. The resulting functions, referred to as the Grant relative permeability functions, are defined by the following equations:

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$$S^* = \frac{(S_l - S_{lr})}{(1 - S_{lr} - S_{sr})} \tag{8.1}$$

$$k_{rl} = (S^*)^4 \tag{8.2}$$

$$k_{rs} = 1 - k_{rl} \tag{8.3}$$

where:
- S_l = liquid saturation;
- S_{lr} = residual liquid saturation;
- S_{sr} = residual steam saturation;
- k_{rl} = liquid relative permeability; and
- k_{rs} = steam relative permeability.

The equation for liquid relative permeability is the same as the Corey relative permeability function for the liquid phase used in petroleum reservoir simulation. The relationship for steam relative permeability is based on the analysis of the Wairakei data which found that the sum of the relative permeabilities of steam and water is close to unity. This result has also been reported where similar data have been analyzed in other two-phase geothermal fields.

The boundary conditions that need to be specified may include the rate of recharge (or discharge) that occurs to (or from) a specific block. In addition, the nature of the boundaries at the periphery of the model also need to be defined. Possible boundary block specifications include one of the following hydraulic conditions: a) a boundary with a given rate of recharge (or discharge); b) a boundary at a constant pressure, or c) a no-flow boundary. The thermal boundary condition is usually one of constant temperature.

The above data regarding the model construction, the initial estimates of reservoir properties, the relative permeability functions and the boundary conditions will be input to the simulation code and the model will be run until the system reaches a quasisteady state. If the system fails to reach a quasisteady state, it is possible that the model has not been set up correctly and appropriate modifications must be made.

Once the system reaches a quasisteady state, the final computed distributions of temperature, pressure and steam saturation will be compared to the observed (or inferred) distributions. If the calculated and observed (or inferred) distributions match within a chosen tolerance, the model will be assumed to be a representative quantitative model of the initial state of the system. If not, the input parameters are modified and further iterations will be made until a match is obtained between the observed and calculated distributions of temperature, pressure and saturation. If no reasonable set of input parameters provides such a match, the model will be considered erroneous and revised accordingly.

After many trial-and-error iterations, a final quantitative model will be derived that satisfactorily matches the initial state and this model will form the basis for analysis of available well test or production data and later for exploitation modeling.

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8.3 Well Test Matching Procedure

Well test data available for matching by simulation include production flow rates and enthalpies and downhole pressure measurements. For the Puna area production characteristics of only well KS-1A have been measured for a significant length of time. In addition, downhole pressures were monitored in the SOH wells at various times during last two years. These data have proven useful in providing both qualitative and quantitative information on the properties of the reservoir encountered in the Puna area. The existing data, plus those to be derived from testing the new PGV wells during the next few months, will be used in the numerical simulation model as a way of further verifying or calibrating the initial state model.

In matching well test data using a numerical simulation model, we will attempt to match as closely as possible measured transients in discharge flow rate and enthalpy from the production wells and measured changes in downhole pressure which occur in response to production or injection. In practice, however, it may not always be possible to obtain close matches due to a number of factors associated with the model construction. For example:

1. Geothermal wells typically produce from multiple feedzones, but it is generally not possible to model each zone individually. The output from the simulation model therefore reflects the average condition of the feed zones and this may not accurately reflect the actual measured well production characteristics.

2. The open interval of observation wells may cover more than one layer of the simulation model. Under these conditions, it is possible that the observation wells may be reacting to

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production and/or injection in multiple layers. The measured pressure response may therefore reflect an averaged signal which involves more than one layer of the simulation model. On the other hand, it is also possible that the pressure front moves through a single permeable zone that cannot be accurately modeled with layers having a significant thickness.

The basic procedure involved in well test matching is presented schematically in figure 8.2. The flow chart indicates that the starting point for well test matching is the initial state model. As mentioned before, the measured downhole temperature and pressure distributions are the major variables used for matching of the initial state. Permeabilities in the x, y and z directions will be varied until a match is obtained to the measured data and it is then assumed that the model provides a fair representation of the reservoir permeability distribution. However, the match is not sensitive to storage terms such as porosity.

To further calibrate the model in terms of reservoir storage, it is necessary to consider how the reservoir reacts to production and injection; in particular, how reservoir pressures and individual well discharge characteristics change with time. Hence, matching of available well test or production data is a very important second phase in the development of a simulation model. When this phase is successfully completed, it increases confidence that the model can be used for forecasting future reservoir behavior under different production scenarios.

When matching well test data it is also possible that some further changes will need to be made to the permeability distribution. Therefore, matching of well test or production data also provides for additional calibration of the model in terms of the permeability distribution. However, it should be noted that well test or production data may be affected by only a relatively small area of the overall reservoir and the resulting changes in porosity or permeability may not necessarily apply to the total simulation model. Therefore, in matching well test or production data it may only be necessary to make changes to hydraulic parameters in blocks located close to the active or observation wells. In areas remote from the drilled wells, the permeability distribution is still primarily based on the matching of the initial state.

If the well test matching is successful but has required significant changes to the permeability distribution, it will be necessary to re-run the initial-state model (figure 8.2) to confirm that the calculated temperature and pressure distributions are still in reasonable agreement with the measured data. If the calculated distributions no longer agree with the measured data, then the modeling process will be continued until a more consistent model is obtained that fits all the available temperature, pressure and well test data.

The process of obtaining a consistent model that continues to match the initial state of the reservoir as well as the discharge characteristics and downhole pressure data requires numerous runs of the simulation model. Overall, this process is the most time consuming part of a numerical simulation reservoir study. After the model has been calibrated in this way, it can be used to accurately forecast future well and reservoir behavior under a variety of plausible production and injection scenarios.

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9. STATUS OF STATEWIDE GEOTHERMAL RESOURCE ASSESSMENT

Exploration and incipient development of the geothermal resources of the KERZ have overshadowed the exploration and assessment efforts underway or contemplated on the other Hawaiian Islands, as well as in other parts of the Big Island. This is appropriate: if the very obvious geothermal potential and significant calculable reserves of the KERZ do not result in commercial production of geothermal electricity, similar but less-strong assessment criteria present in other areas probably will not recommend attractive exploration targets. It now appears that the width of the zone of potential high-temperature production in the KERZ is less than one mile; rift zones in other areas also may potentially be productive only in their central portions, where dike intrusion is active.

The islands of Hawaii, Maui, Lanai, Molokai, Oahu and Kauai are all constructional, composite volcanic features, of which Hawaii is the youngest. The individual volcanoes that make up the islands typically have one or more extensional rift zones extending from their summits, filled by intrusive dike complexes. These dike complexes are thought to contain the combination of heat source and sufficiently permeable rocks that constitute potential high-temperature geothermal reservoirs. If exploration of the KERZ results in significant commercial production, the other areas will become more attractive; however, if permeability is so restricted or unpredictable and drilling conditions so difficult in the KERZ to prevent significant commercial production of electric energy, then the prospects at all the other locations will be reduced to exploration for small-scale, moderate- and low-temperature projects.

Two significant efforts have been made to assess and catalogue the geothermal resources of the principal Hawaiian Islands. A Statewide Geothermal Resource Assessment (SGRA) was published by the DLNR in 1984, principally to help designate geothermal resource sub-zones. At about the same time, Thomas (1984, 1986) presented a table assessing 20 areas, titled "Estimated Probabilities for Occurrence of Geothermal Resources". Thomas' assessment was reviewed by the State's Geothermal Technical Advisory Committee (GEO TAC) in 1991, and revised to reflect newer information and the current philosophy of resource assessment.

A review of the State's "renewable energy resource assessments" also was performed by consultants to DBED (R. Lynette & Associates, 1992). Concise summaries of the principal prior work were presented. Practically no original fieldwork has been done outside the KERZ since 1980, except for some geologic mapping elsewhere on Hawaii (Moore and Truesdell, 1991), publication of an aeromagnetic map of the Kilauea and Mauna Loa volcanoes (Flanigan and others, 1986), and geologic mapping and fluid geochemistry for certain areas in Oahu (Cox and others, 1982).

The latest assessments by the GEO TAC, utilizing the newer information and current philosophy, have resulted in a somewhat more-conservative assessment than was given in 1984. Based on an independent review, GeothermEx proposes the following assessment of the probability for discovery of <u>high</u>-temperature geothermal resources in the several Hawaiian Islands. (To be compatible with the GEO TAC assessment criteria for sub-zone designation, we assume: temperature >125°C at depth <3 km, and with ground elevation <7,000 feet; permeability, is evaluated only where subsurface data exist.)

- <u>Kauai</u>: <5% probability for the existence of a high-temperature resource. The low probability is assigned because major volcanism from the single volcano comprising the island ceased more than 3 million years ago (m.a.), with subordinate weak events not more recent than about 1 m.a. Residual heat of crystallization from shallow intrusive dikes is likely to have been dissipated by 0.1 m.a. Strong hydrothermal systems are no longer likely. There are no known surface manifestations, nor geophysical or geochemical anomalies to guide exploration in the Kauai East and West Rift Zones. No work by the State is recommended except collection of temperature and fluid chemistry data from new wells drilled for water in the region.

- Oahu: 5% probability for the existence of a high-temperature resource. Principal volcanism ended more than 2 m.a. Some weak, post-erosional eruption activity did occur in the vicinity of Koolau and Waianae volcanoes, the two major volcanoes comprising Oahu. Minor geochemical and geophysical (resistivity, seismic, gravity and infrared) anomalies are not considered to be significant indications when compared against the background data in the youthful terrain of a volcanic island. Deep water wells have not found anomalous temperatures or water chemistry. Because the depth (5,000 to 6,500 feet) proposed for the Koolau plug on the basis of gravity and seismic surveys is shallow, and because there are no anomalous subsurface temperatures reported, this suggests that the Koolau plug is not an active heat source. No exploration by the State is recommended except the continued collection of temperature and chemistry data from water wells.

- Molokai: <5% probability for the existence of a high-temperature resource. Magmatic activity constructed two volcanoes, between >2 m.a. and >1 m.a., each volcano being characterized by two rift zones. There are no confirmed temperature, geochemical or geophysical anomalies, other than warm water wells reported on the western part of the island. No exploration by the State is recommended except collection of temperature and chemistry data from all new wells.

- Lanai: <10% probability for the existence of a high-temperature resource. Lanai appears to have been constructed by volcanism more than 1.5 m.a. The only thermal manifestations are warm-water wells. These suggest that exploration for low-temperature resources near Lanai City may be of interest. At this time no assessment the State is encouraged to continue the collection of temperature and chemistry data from water wells. If results are attractive, a further program of geochemical exploration may be warranted at a later time.

- Maui: Maui is the second youngest of the Hawaiian Islands. Two volcanoes, West Maui and Haleakala, make up the island; Haleakala is the younger of the two. West Maui volcanism occurred mainly more than 1.3 m.a. Volcanism from Haleakala volcano has continued through the 18th Century along its southwest rift zone. There is <10% probability for the existence of a high-temperature geothermal resource at West Maui, the reported presence of "warm water" at Olowalu not withstanding.

  There are 3 rift zones associated with Haleakala:

  The southwest rift zone, site of the 1790 eruption, has been the most active zone throughout the construction of Haleakala.

It therefore appears to have the greatest potential for high-temperature geothermal resources. Critical questions are whether a magma chamber still is present, and whether there is active extension and dike intrusion into the southwest rift zone (or indeed into any of the Haleakala rifts). Seismic data have not supported the concept of active rifting and intrusion. Based on this conclusion, there is <20% probability of there being a high-temperature geothermal resource in the southwest rift zone of Haleakala. The east and northwest rift zones, having less evidence of historic volcanism, are considered to have <10% probability of the existence of a high-temperature geothermal resource. Because of these relatively low potentials, the only exploration recommended by the State is the continued collection of temperature and chemistry data from water wells. If results prove encouraging, a program of further geochemical exploration may be proposed. At a still-later date, the drilling of temperature-gradient holes may be desirable.

- Hawaii: There is considerable variation in probability for the existence of high temperature geothermal resources on Hawaii; therefore, an overall summary per cent estimation is not useful.

Hawaii is the youngest of the main Hawaiian Islands. Five volcanoes comprise the island. These, with their minimum ages of main volcanic activity, are:

Kohala: 700,000 to 80,000 years
Mauna Kea: 500,000 to 15,000 years
Hualalai: 400,000 years to 19th Century

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Mauna Loa: active
Kilauea: active

The probabilities of the existence of high-temperature geothermal resources vary from 100% in the KERZ, to >50% in the Kilauea southwest rift zone (KSWRZ), to <20% in the Mauna Loa and Hualalai rift zones, and finally to <10% in the Mauna Kea and Kohala rift zones.

Geophysical information has been interpreted to indicate the existence of magmatic bodies beneath Hualalai; and of course magma occurs below Mauna Loa and Kilauea. Geologically, the upper KSWRZ is being affected by the same magmatic activity as the KERZ; however the crustal stresses, island buttressing effects, and local tectonics may preclude the extension and intrusion of dikes into the KSWRZ necessary to provide heat and permeability to a geothermal reservoir. Based on the foregoing assessment, it is recommended that the only exploration work currently requiring State support is lithologic logging, temperature measurement and analysis of fluid samples from water wells drilled on the Big Island. Major funding should instead be conserved for continued drilling to define the extent and nature of the geothermal resource of the KERZ.

To summarize, the probabilities for the existence of high-temperature geothermal resources are very low for Kauai, Oahu and Molokai; low for Lanai, West Maui, the east and northwest rift zones of Haleakala on Maui, and the Mauna Kea and Kohala rift zone of Hawaii; and moderate for the Mauna Loa and Haulalai rifts of Hawaii. Only in the KERZ and KSWRZ are potentials found to be attractive. Expenditure by the State

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should be limited at present essentially to the KERZ, because of its high potential. Work done in the KERZ is likely to have the additional benefit of defining which exploration methods will be worthwhile elsewhere in the Hawaiian Islands in the future assessment of the State's commercial geothermal potential. Highest priority should continue to be given to definition and characterization of the KERZ.

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TABLES

TABLE 3.1: GROUNDWATER SAMPLES FROM THE KERZ AND SURROUNDINGS, CONCENTRATIONS IN MG/L

GROUP	NAME	DATE	TF	DATASRC	PH	CA	MG	NA	K	CL	HCO3	CO3	SO4	SIO2
Allison Well	ALLISON	-1	100	ENEL(1990)			15.00			840.0				
Allison Well	ALLISON	-1	100	Thomas,USGSPP-1350	7.35	84.0	102.00	1188.0	68.0	2042.0			69.2	24
Allison Well	ALLISON	740131	100	ENEL(1990)										
Allison Well	ALLISON	750107	100	ENEL(1990)			15.00			281.0				
Allison Well	A	750107	100	Iovanetti(1990)			15.00			281.0				
Allison Well	ALLISON	820701	100	ENEL(1990)			102.00			2040.0				
Ashida 1	ASHIDA 1	800625	550	ENEL(1990)			1.45			174.0				
GTW-2	GTW2	740130	181	ENEL(1990)										
GTW-2	GTW2	741214	187	ENEL(1990)										
GTW-3	GTW3	-1	192	ENEL(1990)			55.50			3680.0				
GTW-3	GTW3	-1	199	Thomas,USGSPP-1350	6.85	194.0	122.00	2572.0	378.0	4645.0			314.0	97
GTW-3	GTW3	740910	199	ENEL(1990)										
GTW-3	GTW3	741214	203	ENEL(1990)										
GTW-3	GTW3	741214	190	ENEL(1990)										
GTW-3	GTW3	741216	187	ENEL(1990)										
GTW-3	GEOTH #3	750107		HGP INI.PH.II PROG. 2/76	6.85	76.8	52.00	2050.0	190.0	3274.0	30.0		314.0	97
GTW-3	GTW-IIIa	750107	199	Iovanetti(1990)			52.00			3274.0				
GTW-3	GTW3	750107	199	ENEL(1990)			52.00			3270.0				
GTW-3	GEOTH #3	750721		HGP INI.PH.II PROG. 2/76		81.0	59.00	2000.0	195.0	3410.0			335.0	
GTW-3	GEOTH #3	750721		HGP INI.PH.II PROG. 2/76	1.40	71.0	62.50	1740.0	158.0	2980.0	20.0		317.0	
GTW-3	GTW-IIIb	750721		Iovanetti(1990)			59.00			3410.0				
GTW-3	GTW-IIIc	750721	165	Iovanetti(1990)			62.50			2980.0				
GTW-3	GTW3	750721	165	ENEL(1990)			62.50			2980.0				
GTW-3	GTW3	751231	199	ENEL(1990)			59.00			3410.0				
GTW-3	GTW3	821101	199	ENEL(1990)			137.00			5260.0				
GTW-4	GTW4	821101	95	ENEL(1990)			22.40			390.0				
GTW-4	GTW-IV	910600		Iovanetti(1990)			7.50			72.0				
Hawn Shores	Pahoa	640505		Tilling and Jones (1991)	7.30	4.2	4.80	16.0	2.0	16.0	46.0		6.7	59
Hawn Shores	Pahoa	720522		Tilling and Jones (1991)	7.60	5.8	3.60	23.0	3.2	23.0	56.0		6.9	49
Hawn Shores	HAWN SHORES1	741231	71	ENEL(1990)			3.80			14.0				
Hawn Shores	HAWN SHORES2	741231		ENEL(1990)			4.50			28.0				
Isaac Hale Spr.	Isaac H. Spr	750107		HGP INI.PH.II PROG. 2/76	7.75	32.4	200.00	2020.0	86.0	3534.0	56.0		507.0	82
Isaac Hale Spr.	IHP SPR	751027		HGP INI.PH.II PROG. 2/76		98.0	239.00	2140.0	87.5	3660.0	61.0		552.0	
Kapoho Crater	9d	-1		Iovanetti(1990)			17.00			33.0				

TABLE 3.1: GROUNDWATER SAMPLES FROM THE KERZ AND SURROUNDINGS, CONCENTRATIONS IN MG/L

GROUP	NAME	DATE	TF	DATASRC	PH	CA	MG	NA	K	CL	HCO3	CO3	SO4	SIO2
Kapoho Crater	KAPOHO_CS	-1	77	ENEL(1990)			51.00			84.0				
Kapoho Crater	Kapoho Cone	-1		Tilling and Jones (1991)	7.70	80.0	51.00	73.0	10.5	84.0	551.0		6.8	41
Kapoho Crater	Kapoho	-1	72	Thomas,USGSPP-1350	7.10	65.6	35.20	127.0	15.0	174.0			328.0	54
Kapoho Crater	9c	680315		Iovanetti(1990)			26.50			125.0				
Kapoho Crater	Kapoho	680315		Tilling and Jones (1991)	7.70	48.0	26.00	97.0	14.0	125.0	283.0		5.5	44
Kapoho Crater	Kapoho	700522		Tilling and Jones (1991)	7.00	120.0	96.00	64.0	10.0	72.0	975.0		3.8	39
Kapoho Crater	Kapoho	720303		Tilling and Jones (1991)	8.40	72.0	31.00	57.0	7.6	54.0	393.0		11.0	39
Kapoho Crater	KAPOHO_CS	740130	77	ENEL(1990)										
Kapoho Crater	KAPOHO_CS	741231	77	ENEL(1990)			31.00			110.0				
Kapoho Crater	KAPOHO_CS	741231	77	ENEL(1990)			31.00			170.0				
Kapoho Crater	9a	750106	79	Iovanetti(1990)			37.00			16.9				
Kapoho Crater	KAPOHO_CS	750106	78	ENEL(1990)			37.00			16.9				
Kapoho Crater	9b	750721	72	Iovanetti(1990)			25.70			95.7				
Kapoho Crater	KAPOHO_CS	750721	72	ENEL(1990)			25.70			95.7				
Kapoho Test	9-6c	-1	97	Iovanetti(1990)			24.10			450.0				
Kapoho Test	KAPOHO_LSW	-1	96	ENEL(1990)			24.10			450.0				
Kapoho Test	Airstrip	-1	92	Thomas,USGSPP-1350	7.75	37.6	27.40	241.0	28.0	364.0			211.0	71
Kapoho Test	KAPOHO_LSW	611231	82	ENEL(1990)			17.10			220.0				
Kapoho Test	KAPOHO_LSW	611231	93	ENEL(1990)			17.10			331.0				
Kapoho Test	KAPOHO_LSW	740129	100	ENEL(1990)										
Kapoho Test	KAPOHO_LSW	741213	93	ENEL(1990)										
Kapoho Test	9-6a	750106	91	Iovanetti(1990)			28.00			303.5				
Kapoho Test	KAPOHO_LSW	750106	98	ENEL(1990)			28.00			303.0				
Kapoho Test	9-6b	750722	95	Iovanetti(1990)			27.20			316.0				
Kapoho Test	KAPOHO_LSW	750722	92	ENEL(1990)			27.20			316.0				
Kapoho Test	KAPOHO_LSW	820111	95	ENEL(1990)			22.40			390.0				
Keauohana	9-7b	-1	70	Iovanetti(1990)			5.60			120.0				
Keauohana	KEAUOHANA 1	-1	69	Thomas,USGSPP-1350	7.05	15.4	5.10	95.1	12.4	160.0			28.6	45
Keauohana	Keauohana	-1		Tilling and Jones (1991)	7.30	6.6	3.30	54.0	3.8	70.0	42.0		22.0	41
Keauohana	KEAUOHANA 1	740130	75	ENEL(1990)										
Keauohana	KEAUOHANA 1	741231	75	ENEL(1990)			3.30			70.0				
Keauohana	KEAUOHANA 2	741231	75	ENEL(1990)			5.90			160.0				
Keauohana	9-7a	750106	84	Iovanetti(1990)			6.60			132.2				
Keauohana	KEAUOHANA 1	750106	83	ENEL(1990)			6.60			132.0				
Keauohana	KEAUOHANA 1	750721	69	ENEL(1990)			5.60			120.0				
Keauohana	KEAUOHANA 1	821101	75	ENEL(1990)			3.80			106.0				
MW-1	MW-1	910404		uuri 3910294.pg 4-18-91		22.4	12.82	62.2	7.2					105
MW-1	MW-1	910404		brewer env.svcs 3828		20.6	12.70	58.2	6.4	19.5	36.6		208.0	119
MW-1	MW-1	910412		brewer env.svcs 3828		21.1	12.40	56.7	6.2	20.0	36.0		215.0	119
MW-1	MW-1	910904		brewer env.svcs 5068	7.70	18.4	12.40	58.0	9.0	19.5	36.6		192.0	100

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GROUP	NAME	DATE	TF	DATASRC	PH	CA	MG	NA	K	CL	HCO3	CO3	SO4	SIO2
MW-2	MW-2	910403		uuri 3910295.pg 4-09-91		37.5	17.75	324.3	33.6					26
MW-2	MW-2	910403		brewer env.svcs 3828		27.8	14.60	287.0	18.1	475.0	50.6		123.0	22
MW-2	MW-2	910412		brewer env.svcs 3828		29.7	16.90	311.0	19.1	538.0	57.3		117.0	44
MW-2	MW-2	910904		brewer env.svcs 5068	8.20	31.5	18.10	326.0	24.3	588.0	69.5		73.8	44
Malama-Ki	9-9d	-1	127	Iovanetti(1990)			267.00			6887.0				
Malama-Ki	MALAMA_KI	-1	128	ENEL(1990)			267.00			6890.0				
Malama-Ki	MALAMA_KI	-1	126	Thomas,USGSPP-1350	7.45	293.0	295.00	3333.0	218.0	5380.0			598.0	101
Malama-Ki	Malama-ki	-1		Tilling and Jones (1991)	6.90	182.0	324.00	3090.0		5850.0	262.0		681.0	59
Malama-Ki	9-9c	620906		Iovanetti(1990)			324.00			5850.0				
Malama-Ki	Makama-ki	620906		Tilling and Jones (1991)	6.90	182.0	324.00	3090.0		5850.0	262.0		681.0	59
Malama-Ki	9-9e	620928		Iovanetti(1990)			324.00			5850.0				
Malama-Ki	MALAMA_KI	741213	127	ENEL(1990)										
Malama-Ki	MALAMA_KI	741231	127	ENEL(1990)			324.00			5850.0				
Malama-Ki	MALAMA K.	750107		HGP INI.PH.II PROG. 2/76	7.02	66.8	210.00	2105.0	109.0	3811.0	144.0		471.0	101
Malama-Ki	9-9a	750107	126	Iovanetti(1990)			210.00			2811.0				
Malama-Ki	MALAMA_KI	750107	126	ENEL(1990)			210.00			3810.0				
Malama-Ki	MALAMA K.	750722		HGP INI.PH.II PROG. 2/76	7.45	117.0	293.00	2890.0	149.0	3811.0	128.0		598.0	
Malama-Ki	9-9b	750722		Iovanetti(1990)			293.00			5120.0				
Malama-Ki	MALAMA_KI	750722		ENEL(1990)			293.00			5120.0				
Malama-Ki	MALAMA_KI	830701	131	ENEL(1990)			295.00			5380.0				
Pahoa	Pahoa	-1	74	Thomas,USGSPP-1350	6.65	4.5	3.10	16.7	9.3	4.9			27.3	50
Pahoa	Pahoa 1	-1		Tilling and Jones (1991)	7.70	5.0	4.20	20.0	2.6	20.0	51.0		6.8	54
Pahoa	Pahoa 1	-1		Tilling and Jones (1991)	7.50	3.3	3.30	16.5	3.4	6.0	51.0		12.5	52
Pahoa	Pahoa	720303	73	Tilling and Jones (1991)	7.60	3.9	3.30	16.0	3.3	6.0	51.0		12.0	54
Pahoa	Pahoa	720303	73	Tilling and Jones (1991)	7.40	2.7	3.30	17.0	3.4	6.0	50.0		13.0	50
Pahoa	PAHOA2	740130	73	ENEL(1990)										
Pahoa	PAHOA2	741231	73	ENEL(1990)			2.40			5.8				
Pahoa	9-5a	750106	75	Iovanetti(1990)			2.70			13.5				
Pahoa	PAHOA1	750106		ENEL(1990)			2.70			13.5				
Pahoa	9-5b	750721	73	Iovanetti(1990)			1.90			9.8				
Pahoa	PAHOA1	750721	74	ENEL(1990)			1.90			9.8				
Pahoa	PAHOA1	821101	70	ENEL(1990)			3.10			4.9				
Pahoa	PahVillFrshW	851000	75	Iovanetti(1990)			5.10			4.0				
Pulama	Pulama	631206		Tilling and Jones (1991)	7.40	16.0	31.00	170.0	8.5	345.0	54.0		65.0	72
Pulama	PULAMA	631231	78	ENEL(1990)			31.20			345.0				
Seawater	seawater	-1		ENEL(1990)		450.0	1290.00	9600.0	398.0	19500.0			2200.0	4
RAIN	RAIN	750000		HGP INI.PH.II PROG. 2/76										

EY TO COLUMN HEADINGS [Listed in approximate order, some may not be included in this printout]

ARTS I AND II : SAMPLE BACKGROUND DATA

NUM = sample number
NAME = full name of sample.
DATEHRS = date and time of collection in format yymmdd.hrs
DATASRC = source of analytical data -- laboratory name and date, or report title.
PORT = sample type or source:
BRN = brine from weir or separator.
BLOO = water sample from blooie line, airlift.
WHP = wellhead pressure, g=gauge, a=absolute, psi

SPG = pressure of steam-water separation, psi gauge
SPA = pressure of steam-water separation, psi abs.
SEP_TC = steam separation or sample temperature, deg.C
HT = reported total flow enthalpy, btu/lb
XSTM = steam flow as percent of total

STATUSCOM = comment concerning sample collection and/or status of source at time of collection

ARTS III TO V : ANALYTICAL DATA AND COMMENTS

PHL = sample pH, measured in laboratory, 25degC
CA...MN = species concentrations in mg/l
HCO3,CO3 = total alkalinity as bicarbonate and carbonate, mg/l
TDSS = total dissolved solids by summation of Ca,Mg,Na,K,Li,HCO3,CO3,SO4,Cl,SiO2 and B
COMMENT = additional comments
TRACEANIONS = other anions
TRACECATIONS = other cations

lote: -1 or blank signifies no data. 0.0 indicates below detection limit of analysis,

GEOTHERMEX, INC.
7-10-1992

NAME	DATEHRS	PORT	WHP	DATASRC	STATUSCOM
HGP-A	761202.0000	BRN	-1	Thomas,USGSPP-1350	DOWNHOLE SAMPLE, -1300m
HGP-A	770209.0000	BRN	-1	Thomas,USGSPP-1350	PROBABLY A WEIRBOX SAMPLE; HT FRM #8, XSTM FRM HT
HGP-A	770422.0000	BRN	-1	Thomas,USGSPP-1350	PROBABLY A WEIRBOX SAMPLE; HT FROM #8, XSTM FRM HT
HGP-A	800110.1000	BRN	-1	Thomas (1980)	Brine line frm separator; HT FRM #8, XSTM FRM HT
HGP-A	800111.1300	BRN	-1	Thomas (1980)	Brine line frm separator; HT FRM #8, XSTM FRM HT
HGP-A	800116.0000	BRN	-1	Thomas,USGSPP-1350	HT FRM #8, XSTM FRM HT; tmf=38.39
HGP-A	810612.0000	BRN	-1	Thomas,USGSPP-1350	PROBABLY A WEIRBOX SAMPLE; HT FRM #8, XSTM FRM HT
HGP-A	810904.0000	BRN	-1	Thomas,USGSPP-1350	HT FRM THOMAS TYPICAL XSTM 43% @ 1,200kPa=174psia
HGP-A	811211.0000	BRN	-1	Thomas,USGSPP-1350	PROBABLY A WEIRBOX SAMPLE; HT FRM #8, XSTM FRM HT
HGP-A	820607.0000	BRN	-1	Thomas,USGSPP-1350	HT FRM #8, XSTM FRM HT
HGP-A	821116.0000	BRN	-1	Thomas,USGSPP-1350	HT FRM #8, XSTM FRM HT
HGP-A	830504.0000	BRN	-1	Thomas,USGSPP-1350	HT FRM #8, XSTM FRM HT
HGP-A	831205.0000	BRN	-1	Thomas,USGSPP-1350	HT FRM #8, XSTM FRM HT
HGP-A	840112.0000	BRN	160g	IOVANETTI MMO 871016	
HGP-A	840626.0000	BRN	-1	Thomas,USGSPP-1350	HT FRM #8, XSTM FRM HT
HGP-A	841128.0000	BRN	-1	Thomas,USGSPP-1350	HT FRM #8, XSTM FRM HT
KS-1A	851016.0930	BRN	155g	TPnotesSmpl1002/Anatec	NOTES SAY C.17%BRINE; begin flow test; PRODUCTION SEPARATOR,362F
KS-1A	851019.1700	BRN	155g	TPnotesSmpl1003/Anatec	NOTES SAY C.17%BRINE;PRODUCTION SEPARATOR, 357F
KS-1A	851019.1700	BRN	155g	TPnotesSmpl1004/UURI	NOTES SAY C.17%BRINE; duplicate of smpl 1003
KS-1A	851024.2100	BRN	155g	TPnotesSmpl1005/Anatec	NOTES SAY C.17%BRINE; PRODUCTION SEPARATOR, 365F
KS-1A	851024.2100	BRN	155g	TPnotesSmpl1006/UURI	NOTES SAY C.17%BRINE; PRODUCTION SEPARATOR, 365F
KS-1A	851024.2100	BRN	155g	Thermal Power/Brewer	PRODUCTION SEPARATOR, 365F
KS-1A	851024.2100	BRN	155g	Thermal Power/Brewer	PRODUCTION SEPARATOR, 365F
KS-1A	851026.2100	BRN	80g	TPnotesSmpl1007/Anatec	PRODUCTION SEPARATOR, 315F; XSTM ASSUMES HT 1050BTU/LB
KS-1A	851028.0400	BRN	155g	TPnotesSmpl1009/Anatec	PRODUCTION SEPARATOR, 365F; DURING STEP RATE TEST
KS-1A	851028.2330	BRN	345	TPnotesSmpl1010/Anatec	PRODUCTION SEPARATOR, 363F;XSTM ASSUMES HIGH WHP NO EFFECT ON HT
KS-1A	851029.1330	BRN	640	TPnotesSmpl1011/Anatec	PRODUCTION SEPARATOR, 363F;XSTM ASSUMES HIGH WHP NO EFFECT ON HT
KS-1A	851031.1245	BRN	155g	IOVANETTI MMO 871016	PRODUCTION SEPARATOR, 365F, WHT=368F
KS-2	820609.0000	BRN	175g	IOVANETTI MMO 871016	
KS-3	910000.0000			uuri 3910290.pg 4-16-91	puna geothermal FT-3 BC-013
Lanipuna 1	810422.0000	BLOO	-1	GEx\Amtech0405-81	LAST OF 4 AIR LIFT SMPLS,INCR.SAL.;PERM.ZONE 4000FT 160C
Lanipuna 1	810714.2200	BLOO		GEX/Amtech 0813-81	
Lanipuna 1	810715.0200	BLOO		GEX/Amtech 0813-81	
Lanipuna 1	810715.0300	BLOO		GEX/Amtech 0813-81	
Lanipuna 1	810799.9999	BLOO		GEX/Amtech 0813-81	labeled sample from 4000ft+
Lanipuna 6	840803.1320	BLOO	-1	GEx	unloading well
Lanipuna 6	840808.1600	BLOO	-1	GEx	unloading well
Lanipuna 6	840809.1600	BLOO	-1	GEx	unloading well

M	NAME	DATEHRS	PORT	WHP	DATASRC	STATUSCOM
6	GTW-3	-1.0000			Thomas,USGSPP-1350	
1	GTW-3	750107.0000		-1	HGP INI.PH.II PROG. 2/76	WELL GEOTHERMAL #3, 93C
4	GTW-3	750721.0000		-1	HGP INI.PH.II PROG. 2/76	WELL GEOTHERMAL #3
5	GTW-3	750721.0000		-1	HGP INI.PH.II PROG. 2/76	WELL GEOTHERMAL #3, THIEF SMPL FRM 50-60FT BELOW WTR SURF, 74C
7	Isaac Hale S	750107.0000		-1	HGP INI.PH.II PROG. 2/76	ISAAC HALE PARK SPRING, 36C
8	Isaac Hale S	751027.0000		-1	HGP INI.PH.II PROG. 2/76	ISAAC HALE PARK SPRING
6	Malama-Ki	-1.0000			Thomas,USGSPP-1350	
9	Malama-Ki	620906.0000			Tilling and Jones (1991)	
3	Malama-Ki	750107.0000		-1	HGP INI.PH.II PROG. 2/76	MALAMA KI WELL (WELL 9-9), 52.5C
6	Malama-Ki	750722.0000		-1	HGP INI.PH.II PROG. 2/76	MALAMA KI WELL (WELL 9-9)

	NAME	DATEHRS	PORT	WHP	SPG	SPA	SEP_TC	HT	XSTM	STATUSCOM
	HGP-A	761202.0000	BRN	-1	-1.000	-1.000	-1.0	-1.00	-1.0000	DOWNHOLE SAMPLE, -1300m
	HGP-A	770209.0000	BRN	-1	-1.000	14.930	100.4	710.00	54.5924	PROBABLY A WEIRBOX SAMPLE; HT FRM #8, XSTM FRM HT
	HGP-A	770422.0000	BRN	-1	-1.000	14.930	100.4	710.00	54.5924	PROBABLY A WEIRBOX SAMPLE; HT FROM #8, XSTM FRM HT
	HGP-A	800110.1000	BRN	-1	88.000	102.700	165.4	710.00	46.1617	Brine line frm separator; HT FRM #8, XSTM FRM HT
	HGP-A	800111.1300	BRN	-1	154.000	168.700	186.6	710.00	43.1895	Brine line frm separator; HT FRM #8, XSTM FRM HT
	HGP-A	800116.0000	BRN	-1	-1.000	132.000	175.8	710.00	44.7480	HT FRM #8, XSTM FRM HT; tmf=38.39
	HGP-A	810612.0000	BRN	-1	-1.000	14.930	100.4	710.00	54.5473	PROBABLY A WEIRBOX SAMPLE; HT FRM #8, XSTM FRM HT
	HGP-A	810904.0000	BRN	-1	-1.000	174.000	187.9	710.00	43.0000	HT FRM THOMAS TYPICAL XSTM 43% @ 1,200kPa=174psia
	HGP-A	811211.0000	BRN	-1	-1.000	14.930	100.4	710.00	54.5473	PROBABLY A WEIRBOX SAMPLE; HT FRM #8, XSTM FRM HT
	HGP-A	820607.0000	BRN	-1	-1.000	169.700	186.8	710.00	43.1512	HT FRM #8, XSTM FRM HT
	HGP-A	821116.0000	BRN	-1	-1.000	169.700	186.8	710.00	43.1512	HT FRM #8, XSTM FRM HT
	HGP-A	830504.0000	BRN	-1	-1.000	169.700	186.8	710.00	43.1512	HT FRM #8, XSTM FRM HT
	HGP-A	831205.0000	BRN	-1	-1.000	159.500	184.0	710.00	43.5471	HT FRM #8, XSTM FRM HT
	HGP-A	840112.0000	BRN	160g	-1.000	-1.000	-1.0	-1.00	-1.0000	
	HGP-A	840626.0000	BRN	-1	-1.000	159.500	184.0	710.00	43.5471	HT FRM #8, XSTM FRM HT
	HGP-A	841128.0000	BRN	-1	-1.000	159.500	184.0	710.00	43.5471	HT FRM #8, XSTM FRM HT
	KS-1A	851016.0930	BRN	155g	160.000	174.700	188.1	-1.00	83.0000	NOTES SAY C.17%BRINE; begin flow test; PRODUCTION SEPARATOR,362F
	KS-1A	851019.1700	BRN	155g	156.000	170.700	187.1	-1.00	83.0000	NOTES SAY C.17%BRINE;PRODUCTION SEPARATOR, 357F
	KS-1A	851019.1700	BRN	155g	156.000	170.700	187.1	-1.00	83.0000	NOTES SAY C.17%BRINE; duplicate of smpl 1003
	KS-1A	851024.2100	BRN	155g	155.000	169.700	186.8	-1.00	83.0000	NOTES SAY C.17%BRINE; PRODUCTION SEPARATOR, 365F
	KS-1A	851024.2100	BRN	155g	155.000	169.700	186.8	-1.00	83.0000	NOTES SAY C.17%BRINE; PRODUCTION SEPARATOR, 365F
	KS-1A	851024.2100	BRN	155g	155.000	169.700	186.8	1054.00	83.3899	PRODUCTION SEPARATOR, 365F
	KS-1A	851024.2100	BRN	155g	155.000	169.700	186.8	1054.00	83.3899	PRODUCTION SEPARATOR, 365F
	KS-1A	851026.2100	BRN	80g	72.000	86.700	158.7	-1.00	84.9972	PRODUCTION SEPARATOR, 315F; XSTM ASSUMES HT 1050BTU/LB
	KS-1A	851028.0400	BRN	155g	154.000	168.700	186.6	-1.00	83.0000	PRODUCTION SEPARATOR, 365F; DURING STEP RATE TEST
	KS-1A	851028.2330	BRN	345	153.000	167.700	186.3	-1.00	83.0000	PRODUCTION SEPARATOR, 363F;XSTM ASSUMES HIGH WHP NO EFFECT ON HT
	KS-1A	851029.1330	BRN	640	153.000	167.700	186.3	-1.00	83.0000	PRODUCTION SEPARATOR, 363F;XSTM ASSUMES HIGH WHP NO EFFECT ON HT
	KS-1A	851031.1245	BRN	155g	153.000	167.700	186.3	1042.00	82.0264	PRODUCTION SEPARATOR, 365F, WHT=368F
2	KS-2	820609.0000	BRN	175g	-1.000	-1.000	-1.0	-1.00	-1.0000	
4	KS-3	910000.0000			-1.000	-1.000	-1.0	-1.00	-1.0000	puna geothermal FT-3 BC-013
5	Lanipuna 1	810422.0000	BLOO	-1	-1.000	-1.000	-1.0	-1.00	-1.0000	LAST OF 4 AIR LIFT SMPLS,INCR.SAL.;PERM.ZONE 4000FT 160C
6	Lanipuna 1	810714.2200	BLOO		-1.000	-1.000	-1.0	-1.00	-1.0000	
7	Lanipuna 1	810715.0200	BLOO		-1.000	-1.000	-1.0	-1.00	-1.0000	
8	Lanipuna 1	810715.0300	BLOO		-1.000	-1.000	-1.0	-1.00	-1.0000	
9	Lanipuna 1	810799.9999	BLOO		-1.000	-1.000	-1.0	-1.00	-1.0000	labeled sample from 4000ft+
1	Lanipuna 6	840803.1320	BLOO	-1	-1.000	-1.000	-1.0	-1.00	-1.0000	unloading well
3	Lanipuna 6	840808.1600	BLOO	-1	-1.000	-1.000	-1.0	-1.00	-1.0000	unloading well
5	Lanipuna 6	840809.1600	BLOO	-1	-1.000	-1.000	-1.0	-1.00	-1.0000	unloading well

UM	NAME	DATEHRS	PORT	WHP	SPG	SPA	SEP_TC	HT	XSTM	STATUSCOM
56	GTW-3	-1.0000			-1.000	-1.000	93.0	-1.00	-1.0000	
61	GTW-3	750107.0000		-1	-1.000	-1.000	-1.0	-1.00	-1.0000	WELL GEOTHERMAL #3, 93C
64	GTW-3	750721.0000		-1	-1.000	-1.000	-1.0	-1.00	-1.0000	WELL GEOTHERMAL #3
65	GTW-3	750721.0000		-1	-1.000	-1.000	-1.0	-1.00	-1.0000	WELL GEOTHERMAL #3, THIEF SMPL FRM 50-60FT BELOW WTR SURF, 74C
77	Isaac Hale S	750107.0000		-1	-1.000	-1.000	-1.0	-1.00	-1.0000	ISAAC HALE PARK SPRING, 36C
78	Isaac Hale S	751027.0000		-1	-1.000	-1.000	-1.0	-1.00	-1.0000	ISAAC HALE PARK SPRING
26	Malama-Ki	-1.0000			-1.000	-1.000	52.2	-1.00	-1.0000	
29	Malama-Ki	620906.0000			-1.000	-1.000	-1.0	-1.00	-1.0000	
33	Malama-Ki	750107.0000		-1	-1.000	-1.000	-1.0	-1.00	-1.0000	MALAMA KI WELL (WELL 9-9), 52.5C
36	Malama-Ki	750722.0000		-1	-1.000	-1.000	-1.0	-1.00	-1.0000	MALAMA KI WELL (WELL 9-9)

I	NAME	DATEHRS	BASIS	PHL	CA	MG	NA	K	LI	HCO3	CO3	SO4	CL	F_	SIO2	B	TDSS
1	HGP-A	761202.0000	SAMPLE	-1.00	17.3	0.70	480.0	85.0	-1.00	-1.0	-1.0	-1.0	920.0	-1.00	740	-1.0	2243
2	HGP-A	770209.0000	SAMPLE	-1.00	30.1	0.10	720.0	135.0	-1.00	-1.0	-1.0	-1.0	1610.0	-1.00	-1	-1.0	2495
3	HGP-A	770422.0000	SAMPLE	-1.00	72.2	0.10	1480.0	277.0	-1.00	-1.0	-1.0	-1.0	3190.0	-1.00	-1	-1.0	5019
4	HGP-A	800110.1000	SAMPLE	-1.00	16.3	0.00	1430.0	200.0	-1.00	-1.0	-1.0	50.0	2390.0	-1.00	865	-1.0	4951
5	HGP-A	800111.1300	SAMPLE	-1.00	33.2	0.00	1463.0	211.0	-1.00	-1.0	-1.0	60.0	2450.0	-1.00	792	-1.0	5009
6	HGP-A	800116.0000	SAMPLE	-1.00	33.9	0.01	1520.0	224.0	-1.00	-1.0	-1.0	69.0	2593.0	-1.00	832	-1.0	5272
7	HGP-A	810612.0000	SAMPLE	-1.00	25.5	0.01	900.0	200.0	-1.00	-1.0	-1.0	69.0	2065.0	-1.00	1198	-1.0	4458
8	HGP-A	810904.0000	SAMPLE	-1.00	66.5	0.03	1890.0	295.0	-1.00	-1.0	-1.0	69.0	3622.0	-1.00	860	-1.0	6803
9	HGP-A	811211.0000	SAMPLE	-1.00	33.0	0.01	1590.0	300.0	-1.00	-1.0	-1.0	69.0	2763.0	-1.00	1004	-1.0	5759
0	HGP-A	820607.0000	SAMPLE	-1.00	122.5	0.05	3120.0	525.0	-1.00	-1.0	-1.0	69.0	5667.0	-1.00	803	-1.0	10307
1	HGP-A	821116.0000	SAMPLE	-1.00	217.0	0.10	3940.0	650.0	-1.00	-1.0	-1.0	69.0	7029.0	-1.00	829	-1.0	12734
2	HGP-A	830504.0000	SAMPLE	-1.00	270.0	0.15	4220.0	675.0	-1.00	-1.0	-1.0	69.0	7965.0	-1.00	805	-1.0	14004
3	HGP-A	831205.0000	SAMPLE	-1.00	319.0	0.21	4650.0	763.0	-1.00	-1.0	-1.0	24.0	8827.0	-1.00	825	-1.0	15408
4	HGP-A	840112.0000	SAMPLE	6.60	358.0	0.26	4927.0	756.0	1.10	18.5	0.0	24.0	8968.0	0.25	386	4.3	15434
5	HGP-A	840626.0000	SAMPLE	-1.00	489.0	0.25	4840.0	773.0	-1.00	-1.0	-1.0	15.0	8900.0	-1.00	885	-1.0	15902
6	HGP-A	841128.0000	SAMPLE	-1.00	399.0	0.20	5420.0	733.0	-1.00	-1.0	-1.0	4.5	9514.0	-1.00	913	-1.0	16984
9	KS-1A	851016.0930	SAMPLE	5.80	950.0	1.20	9750.0	2500.0	8.40	15.0	0.0	25.0	19000.0	1.10	850	11.0	33103
0	KS-1A	851019.1700	SAMPLE	4.80	900.0	1.70	10000.0	2500.0	8.20	0.0	0.0	11.0	19500.0	1.00	1000	10.0	33931
1	KS-1A	851019.1700	SAMPLE	4.80	800.0	0.00	9428.0	2308.0	7.33	1.2	0.0	15.0	18800.0	0.93	870	8.8	32238
2	KS-1A	851024.2100	SAMPLE	4.60	860.0	1.70	10000.0	2500.0	8.60	0.0	0.0	20.0	21000.0	0.91	1500	7.0	35897
3	KS-1A	851024.2100	SAMPLE	4.60	838.0	0.00	9805.0	2400.0	7.68	1.2	0.0	14.0	19465.0	-1.00	1390	8.4	33929
4	KS-1A	851024.2100	SAMPLE	8.32	903.0	2.15	10720.0	2940.0	-1.00	3.5	0.0	25.0	19645.0	0.75	900	5.5	35142
5	KS-1A	851024.2100	SAMPLE	5.42	853.0	2.19	11030.0	-1.0	-1.00	3.3	0.0	-1.0	19620.0	0.76	-1	-1.0	31507
6	KS-1A	851026.2100	SAMPLE	4.70	1100.0	2.40	12500.0	2400.0	10.00	0.0	0.0	7.2	24000.0	1.10	1700	14.0	41734
7	KS-1A	851028.0400	SAMPLE	-1.00	870.0	1.80	9500.0	2500.0	8.40	-1.0	-1.0	-1.0	-1.0	-1.00	-1	-1.0	12880
8	KS-1A	851028.2330	SAMPLE	3.80	710.0	1.50	8100.0	2100.0	6.90	0.0	0.0	7.2	17000.0	0.76	1000	8.7	28934
9	KS-1A	851029.1330	SAMPLE	3.80	590.0	0.60	6700.0	1800.0	3.90	0.0	0.0	6.3	13000.0	0.69	950	7.2	23058
1	KS-1A	851031.1245	SAMPLE	4.50	920.0	2.00	10000.0	2700.0	8.70	0.0	0.0	-1.0	21000.0	0.86	2000	11.0	36642
2	KS-2	820609.0000	SAMPLE	-1.00	2400.0	20.00	15000.0	3600.0	12.00	-1.0	-1.0	-1.0	-1.0	0.80	1100	25.0	22157
4	KS-3	910000.0000	SAMPLE	3.58	3948.9	58.32	22674.9	5288.0	16.28	0.0	0.0	6.0	50100.0	2.00	1399	23.3	86283
5	Lanipuna 1	810422.0000	SAMPLE	7.00	1530.0	0.50	8578.0	8.1	0.64	92.0	0.0	112.0	15700.0	0.27	53	5.4	26033
6	Lanipuna 1	810714.2200	SAMPLE	6.88	794.0	0.16	5950.0	399.0	0.81	45.3	0.0	89.8	10500.0	0.28	201	3.5	17961
7	Lanipuna 1	810715.0200	SAMPLE	7.14	1160.0	0.85	6830.0	505.0	0.95	56.6	0.0	59.1	13700.0	0.38	150	5.3	22439
8	Lanipuna 1	810715.0300	SAMPLE	4.48	1590.0	0.62	8240.0	983.0	1.66	0.0	0.0	57.8	17500.0	0.27	284	16.4	28673
9	Lanipuna 1	810799.9999	SAMPLE	6.55	1350.0	0.23	7800.0	840.0	1.53	9.3	0.0	70.9	16400.0	0.14	0	7.3	26475
1	Lanipuna 6	840803.1320	SAMPLE	8.40	1393.0	14.00	7750.0	397.0	-1.00	50.0	0.0	430.0	14400.0	-1.00	137	3.5	24549
3	Lanipuna 6	840808.1600	SAMPLE	8.20	1480.0	14.00	8230.0	408.0	-1.00	39.0	0.0	430.0	15400.0	-1.00	133	3.4	26118
5	Lanipuna 6	840809.1600	SAMPLE	8.30	1524.0	15.00	8380.0	420.0	-1.00	34.0	0.0	403.0	15600.0	-1.00	135	3.4	26497

UM	NAME	DATEHRS	BASIS	PHL	CA	MG	NA	K	LI	HCO3	CO3	SO4	CL	F_	SIO2	B	TDSS
56	GTW-3	-1.0000	SAMPLE	6.85	194.0	122.00	2572.0	378.0	-1.00	-1.0	-1.0	314.0	4645.0	-1.00	97	-1.0	-1
61	GTW-3	750107.0000	SAMPLE	6.85	76.8	52.00	2050.0	190.0	-1.00	30.0	0.0	314.0	3274.0	-1.00	97	-1.0	6068
64	GTW-3	750721.0000	SAMPLE	-1.00	81.0	59.00	2000.0	195.0	-1.00	-1.0	-1.0	335.0	3410.0	-1.00	-1	-1.0	6080
65	GTW-3	750721.0000	SAMPLE	1.40	71.0	62.50	1740.0	158.0	-1.00	20.0	0.0	317.0	2980.0	-1.00	-1	-1.0	5338
77	Isaac Hale S	750107.0000	SAMPLE	7.75	32.4	200.00	2020.0	86.0	-1.00	56.0	0.0	507.0	3534.0	-1.00	82	-1.0	6489
78	Isaac Hale S	751027.0000	SAMPLE	-1.00	98.0	239.00	2140.0	87.5	-1.00	61.0	0.0	552.0	3660.0	-1.00	-1	-1.0	6807
26	Malama-Ki	-1.0000	SAMPLE	7.45	293.0	295.00	3333.0	218.0	-1.00	-1.0	-1.0	598.0	5380.0	-1.00	101	-1.0	-1
29	Malama-Ki	620906.0000	SAMPLE	6.90	182.0	324.00	3090.0	-1.0	-1.00	262.0	-1.0	681.0	5850.0	1.50	59	-1.0	10300
33	Malama-Ki	750107.0000	SAMPLE	7.02	66.8	210.00	2105.0	109.0	-1.00	144.0	0.0	471.0	3811.0	-1.00	101	-1.0	6945
36	Malama-Ki	750722.0000	SAMPLE	7.45	117.0	293.00	2890.0	149.0	-1.00	128.0	0.0	598.0	3811.0	-1.00	-1	-1.0	9230

	NAME	DATEHRS	H2S	NH4	FE	BR	AS_	MN	COMMENT
	HGP-A	761202.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	770209.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	770422.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	800110.1000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	800111.1300	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	800116.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	810612.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	810904.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	811211.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	820607.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	821116.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	830504.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	831205.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	840112.0000	15.00	0.00	0.00	44.0	0.09	0.2	
	HGP-A	840626.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
	HGP-A	841128.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
9	KS-1A	851016.0930	6.00	0.17	0.30	20.0	0.40	4.0	ANALYSES IN MG/L; DENSITY 1.02; alternate copy has 9900mg/l Na
0	KS-1A	851019.1700	3.40	0.19	3.00	40.0	0.50	8.1	ANALYSES IN MG/L; DENSITY 1.02; Cl=ave 2 det. 19000 & 20000
1	KS-1A	851019.1700	3.20	15.00	-1.00	53.0	0.30	7.8	ANALYSES IN ppm; DENSITY 1.016; Cl=ave 2 det. 18500 & 19100
2	KS-1A	851024.2100	7.80	0.13	8.60	80.0	0.60	8.1	ANALYSES IN MG/L; DENSITY 1.03; Cl = also reptd 17000 & 20000
3	KS-1A	851024.2100	7.20	0.13	9.77	74.0	0.44	8.8	ANALYSES IN ppm; DENSITY 1.017; Cl = ave two det. 19230 & 19700
4	KS-1A	851024.2100	30.00	0.21	8.32	-1.0	0.06	13.8	SP.GR = 1.02345
5	KS-1A	851024.2100	26.00	-1.00	10.01	-1.0	0.06	13.3	
6	KS-1A	851026.2100	2.20	0.12	8.10	100.0	0.80	9.5	ANAL.IN MG/L; DEN. 1.03; Na=ave 12000&13000; K 2400? OR 2900?
7	KS-1A	851028.0400	4.30	0.11	5.40	-1.0	0.50	8.0	ANALYSES IN MG/L
8	KS-1A	851028.2330	8.30	-1.00	6.50	70.0	0.40	7.6	ANALYSES IN MG/L
9	KS-1A	851029.1330	7.80	0.10	3.40	50.0	0.40	5.8	ANALYSES IN MG/L
1	KS-1A	851031.1245	5.20	0.10	8.40	80.0	-1.00	8.5	ANALYSES IN MG/L; DENSITY 1.03
2	KS-2	820609.0000	-1.00	-1.00	1100.00	1.5	0.00	110.0	
4	KS-3	910000.0000	-1.00	-1.00	2354.11	-1.0	0.00	195.5	
5	Lanipuna 1	810422.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	MG/L CONCENTRATIONS
6	Lanipuna 1	810714.2200	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	lab reported difficulty obtaining reproducible SiO2 values
7	Lanipuna 1	810715.0200	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	lab reported diff.obtaining reproducible SiO2 values
8	Lanipuna 1	810715.0300	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	lab reported diff.obtaining reproducible SiO2 values
9	Lanipuna 1	810799.9999	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
1	Lanipuna 6	840803.1320	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
3	Lanipuna 6	840808.1600	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
5	Lanipuna 6	840809.1600	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	prob.seawater altd and diluted 25-30% w/cool component

IUM	NAME	DATEHRS	H2S	NH4	FE	BR	AS_	MN	COMMENT
56	GTW-3	-1.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
61	GTW-3	750107.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	TRITIUM = 10.3 +- 0.8 TU
64	GTW-3	750721.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	TRITIUM = 7.3 +- 0.9 TU
65	GTW-3	750721.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
77	Isaac Hale S	750107.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	TRITIUM = 8.5 +- 1.0 TU
78	Isaac Hale S	751027.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	CA VALUE REPORTED SUSPECT.
26	Malama-Ki	-1.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
29	Malama-Ki	620906.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	
33	Malama-Ki	750107.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	TRITIUM = 15.6 +- 1.6 TU
36	Malama-Ki	750722.0000	-1.00	-1.00	-1.00	-1.0	-1.00	-1.0	TRITIUM = 8.6 +- 1.0 TU

Table 4.1 Deep Wells Drilled in the KERZ

Well Name	Operator	Year Drilled	Depth, Feet	Maximum Temperature, °F	Result and Status
HGP-A	State of Hawaii	1976	6,210	680	Field discovery well - produced up to 3 MW between 1982-89 - shut-in
Ashida 1	Barnwell-WRI	1981	8,300	550	Exploratory - dry - plugged
Lanipuna 1	Barnwell-WRI	1981	8,389	685+	Production test - dry - may be hottest well in field - plugged
KS-1	Thermal Power	1981	7,290	650	Production test - tested at 3.2 MW - damaged - plugged
KS-2	Thermal Power	1982	8,005	670+	Production test - tested at 2 MW - damaged - plugged
Lanipuna 1 Sidetrack	Barnwell-WRI	1983	6,271	429	Production test - sidetrack of Lanipuna 1 - probably outside of reservoir - plugged
Lanipuna 6	Barnwell-WRI	1984	4,956	335	Production test - coolest hole - probably outside of reservoir - possible injector - suspended
KS-1A	Thermal Power	1985	6,505	670	Production test - tested at 3 MW - damaged - possible injector - plugged
KS-3	PGV	1990-91	7,406	664+	Production test - tested at 3.2 MW - may be converted to injection - shut-in
SOH-4	State of Hawaii	1990	6,562	576	Scientific observation - may have entered reservoir - monitoring
KMERZ A-1	True/Mid-Pacific Geothermal	1990-91	8,741 (A-1 Sidetrack) 8,651 (A-1)	635	Exploratory - original hole plus sidetrack and 3 redrills - logged and tested - deepest hole in rift zone - steam entries reported - suspended
KS-7	PGV	1991	1,678	500+	Injection test - steam/gas blowout - plugged
SOH-1	State of Hawaii	1991	5,526	408	Scientific observation - probably outside of reservoir - monitoring
SOH-2	State of Hawaii	1991	6,802	661	Scientific observation - may have entered reservoir - monitoring
KS-8	PGV	1991-92	3,488	630+	Production test - steam/gas blowout - potentially large producer - suspended during rework operations

TABLE 5.1 : SAMPLES FROM WELLS HGP-A AND KS-1A CORRECTED FOR STEAM LOSS FROM QUARTZ TEMPERATURE ENTHALPY

NAME	DATEHRS	PHL	CA	MG	NA	K	LI	HCO3	CO3	SO4	CL	F_	SIO2	B
HGP-A	761202.0000	-1.00	-1.0	-1.00	-1.0	-1.0	-1.00	-1.0	-1.0	-1.0	-1.0	-1.00	-1	-1.0
"	770209.0000	-1.00	-1.0	-1.00	-1.0	-1.0	-1.00	-1.0	-1.0	-1.0	-1.0	-1.00	-1	-1.0
"	770422.0000	-1.00	-1.0	-1.00	-1.0	-1.0	-1.00	-1.0	-1.0	-1.0	-1.0	-1.00	-1	-1.0
"	800110.1000	-1.00	11.8	0.00	1032.6	144.4	-1.00	-1.0	-1.0	36.1	1725.7	-1.00	625	-1.0
"	800111.1300	-1.00	25.5	0.00	1124.1	162.1	-1.00	-1.0	-1.0	46.1	1882.5	-1.00	609	-1.0
"	800116.0000	-1.00	25.2	0.01	1129.8	166.5	-1.00	-1.0	-1.0	51.3	1927.3	-1.00	618	-1.0
"	810612.0000	-1.00	14.8	0.00	521.7	115.9	-1.00	-1.0	-1.0	40.0	1197.1	-1.00	694	-1.0
"	810904.0000	-1.00	49.8	0.02	1414.6	220.8	-1.00	-1.0	-1.0	51.6	2710.8	-1.00	644	-1.0
"	811211.0000	-1.00	20.5	0.01	989.4	186.7	-1.00	-1.0	-1.0	42.9	1719.3	-1.00	625	-1.0
"	820607.0000	-1.00	93.8	0.04	2387.8	401.8	-1.00	-1.0	-1.0	52.8	4337.1	-1.00	615	-1.0
"	821116.0000	-1.00	164.3	0.08	2982.7	492.1	-1.00	-1.0	-1.0	52.2	5321.2	-1.00	628	-1.0
"	830504.0000	-1.00	206.4	0.12	3226.5	516.1	-1.00	-1.0	-1.0	52.8	6089.8	-1.00	615	-1.0
"	831205.0000	-1.00	240.9	0.16	3511.1	576.1	-1.00	-1.0	-1.0	18.1	6665.1	-1.00	623	-1.0
"	840112.0000	6.60	-1.0	-1.00	-1.0	-1.0	-1.00	-1.0	-1.0	-1.0	-1.0	0.25	-1	-1.0
"	840626.0000	-1.00	360.1	0.18	3563.8	569.2	-1.00	-1.0	-1.0	11.0	6553.2	-1.00	652	-1.0
"	841128.0000	-1.00	290.4	0.15	3944.7	533.5	-1.00	-1.0	-1.0	3.3	6924.4	-1.00	664	-1.0
KS-1A	851016.0930	5.80	714.2	0.90	7329.9	1879.5	6.31	11.3	0.0	18.8	14283.9	1.10	639	8.3
"	851019.1700	4.80	633.3	1.20	7036.6	1759.1	5.77	0.0	0.0	7.7	13721.3	1.00	704	7.0
"	851019.1700	4.80	595.5	0.00	7018.3	1718.1	5.46	0.9	0.0	11.2	13994.9	0.93	648	6.6
"	851024.2100	4.60	-1.0	-1.00	-1.0	-1.0	-1.00	-1.0	-1.0	-1.0	-1.0	0.91	-1	-1.0
"	851024.2100	4.60	-1.0	-1.00	-1.0	-1.0	-1.00	-1.0	-1.0	-1.0	-1.0	-1.00	-1	-1.0
"	851024.2100	8.32	663.4	1.58	7875.4	2159.9	-1.00	2.6	0.0	18.4	14432.2	0.75	661	4.0
"	851024.2100	5.42	-1.0	-1.00	-1.0	-1.0	-1.00	-1.0	-1.0	-1.0	-1.0	0.76	-1	-1.0
"	851026.2100	4.70	-1.0	-1.00	-1.0	-1.0	-1.00	-1.0	-1.0	-1.0	-1.0	1.10	-1	-1.0
"	851028.0400	-1.00	-1.0	-1.00	-1.0	-1.0	-1.00	-1.0	-1.0	-1.0	-1.0	-1.00	-1	-1.0
"	851028.2330	3.80	499.0	1.05	5692.8	1475.9	4.85	0.0	0.0	5.1	11947.8	0.76	703	6.1
"	851029.1330	3.80	424.0	0.43	4814.9	1293.6	2.80	0.0	0.0	4.5	9342.3	0.69	683	5.2
"	851031.1245	4.50	-1.0	-1.00	-1.0	-1.0	-1.00	-1.0	-1.0	-1.0	-1.0	0.86	-1	-1.0

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Table 5.2. Rock Temperatures Interpreted from Downhole Temperature Surveys

Temperature, °F (Estimated)	Elevation (feet, msl)						
	-1,000	-2,000	-3,000	-4,000	-5,000	-6,000	-7,000
Lanipuna 1	100	210	295	385	450	520	680
Lanipuna 1 Sidetrack	118	175	280	385	415	330	--
Lanipuna 6	150	235	320	255	~270	--	--
HGP-A	215	410	510	550	555	~660	--
KS-1/KS-1A	175	336	483	580	640	~660	--
KS-2	110	240	415	520	580	640	--

Note: ~ = value derived from downward projection of gradient

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Table 5.3 Pressures at -5,000 feet msl and Vertical Pressure Gradients Between -4,000 and -5,000 Feet msl

Well	Pressure, psig at -5,000 feet msl (Projected Where Necessary)	Vertical Pressure Gradient, psi/foot, -4,000 to -5,000 feet msl
Lanipuna 1 Sidetrack	2,620	0.44
HGP-A	2,180	0.42
KS-1A	1,980	0.33
KS-2	2,200	0.33

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Table 6.1: Summary of Discharge Parameters, Wells KS-1, KS-2, KS-1A and KS-3

Well	Wellhead Pressure (psia)	Enthalpy (BTU/lb)	Total Flow Rate (KPH)	Power Rating* (MW)
KS-1 (11-28 August 1982)				
	122	dry steam	71.0	-
	126	dry steam	78.9	-
	233	dry steam	59.7	3.2
	168	dry steam	69.6	-
	154	dry steam	69.5	-
	133	dry steam	68.0	-
	193	dry steam	66.4	-
	131	dry steam	73.0	-
	216	dry steam	59.7	3.1
	129	dry steam	72.5	-
KS-2 (28 July-2 August 1982)				
	163	wet steam	37.8	-
	225	dry steam	19.0	1.0
	188	dry steam	35.2	-
KS-1A (7-31 October 1985)				
	170	1038	74.9	-
	94	1049	70.9	-
	124	1038	77.5	-
	170	1034	79.1	-
	217	1021	78.1	3.2
	271	1009	76.6	3.1
	314	999	75.5	3.0
	364	976	74.7	2.9
	418	980	73.5	2.9
	486	960	68.4	2.6
	514	955	70.6	2.6
	679	906	63.9	2.2
	920	782	49.3	1.3
	168	1046	80.7	-

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Table 6.1 (cont'd)

Well	Wellhead Pressure (psia)	Enthalpy (BTU/lb)	Total Flow Rate (KPH)	Power Rating* (MW)
KS-3 (25-31 March 1991)				
	190	937	92.9	-
	103	951	90.3	-
	315	912	83.1	2.9
	119	970	88.1	-
	450	884	75.2	2.5
	615	856	72.1	2.3
	237	957	85.2	3.2
	241	957	85.2	3.2

* based on separator pressure of 225 psia and steam consumption of 18.854 KPH per MW.

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Table 7.1

Cost Estimation for Drilling One Directional
5-7/8-Inch-Diameter Well at Puna KGRA

Vertical well planned for 7,500 feet maximum depth, with 5-7/8-inch completion diameter. Premise is 60 days average time to total depth.

Item	Cost	Notes
Mobilization, demobilization, each (1 well program)	$ 100,000	Based on $100,000 each movement within Hawaii; moves on the same pad are budgeted at $30,000 and moves between pads at $75,000 each.
Contract drilling	390,000	Based on $6,500 daily average cost
Fuel	75,000	Based on $1,250 daily average cost
BOP, rental	35,000	Rotating head only; other BOP equipment included in daily drilling cost
Bits	175,000	
Bottomhole assemblies	85,000	Includes hole openers, reamers, stabilizers, shock absorbing jars, etc.
CASING (FOB - HILO)		
20" x 30' (conductor)	3,400	K-55, 106 lb/ft, BTC
13-3/8" x 1,000' (surface)	35,000	L-80, 68 lb/ft. BTC
9-5/8" x 2,000' (intermediate)	50,000	L-80, 57 lb/ft, VAM
7-5/8" x 4,000' (production)	80,000	L-80, 42.8 lb/ft, VAM
4-1/2" x 3,500' (slotted)	102,000	L-80, 15.1 lb/ft, HSFJ
Cement	80,000	
Casing services	50,000	
Mud, chemicals	75,000	
Air, chemicals	40,000	

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Item	Cost	Notes
Drill string	30,000	Hard banding, straightening, inspection, replacement
Other tools	15,000	Shoes, floats, hangers, etc.
Well head	30,000	Complete, all valves, casing head and expansion spool
Mud logging	50,000	Includes H_2S monitoring, abatement
Welding support, service	20,000	
Directional services (based on 15 days directional work)	55,000	
Drillpipe and collar repair	20,000	
Fishing, other emergencies	50,000	No major losses assumed
Supervision and engineering	45,000	
Geology and management	40,000	
Downhole logging	10,000	
Administration, accounting	5,000	
Reporting	3,000	Drafting, secretarial, reproduction, shipping
Insurance premiums	25,000	
Water hauling	40,000	
Cellar conductor, mouse (and rat) hole	20,000	
Site trash and sanitary	3,000	
Hauling, trucking, forklifting	25,000	Compressors, collars, subs, tools
Miscellaneous	20,000	Trailers, utilities, tools
TOTAL	$ 1,881,400	

Table 7.2

CASING AND CEMENTING PROGNOSIS

SIZE	DEPTH	WELL
13-3/8"	1,000′	Puna-Exploration

INTERVAL	WEIGHT LB/FT	GRADE	JOINT TYPE	CALCULATED SAFETY FACTORS		
				BURST	COLL.	TENSION
0-1,000′	72	L-80	Buttress	3.79	5.35	4.94

DESIGN CONDITIONS

Surface Burst Pressure	800	psi	Outside mud wt. (collapse)	9.6	ppg
Inside Mud Weight (Burst)	9.6	ppg	Inside mud wt. (collapse)	0.0	ppg
Outside Mud Weight (Burst)	8.6	ppg	Form. press. grad. at shoe (collapse)	--	ppg

CEMENT PROGRAM

SLURRY DESCRIPTION AND PROPERTIES

SLURRY DESCRIPTION: Class "G" cement, 1:1 Perlite, 40% Silica Flour, 3% Gel and 0.65% CFR-2. Tail slurry; Class "G" cement, 40% Silica Flour and 0.5% CFR-2. Retard as needed for BHT.

DESIRED TOP: Surface | EXCESS: 100%

SLURRY VOL.- CU. FT.	1,400	300	
SLURRY YIELD - CU. FT./SACK	2.12	1.62	
SLURRY DENSITY - PPG	13.8	15.4	
THICKENING TIME	2-3 hrs.	2-3 hrs.	
COMPRESSIVE STRENGTH - PSI (HRS)	1,100 (24 hrs)	2,320 (8 hrs)	

RUNNING AND CEMENTING INSTRUCTIONS

Shoe, collars

1. Halliburton float shoe, welded and Halliburton float collar, two joints above shoe.
2. Use Bakerlock on bottom 3 joints; tack weld bottom of collars.
3. Use stab-in type float collar.
4. Use hydraulically operated stage cementer if needed. Locate cementer ± 100 feet above largest loss circulation zone.

Centralizers - number, type and spacing

1. One centralizer above shoe; one in middle of the first joint, then one on every third joint to 600′, then one every 200 ft.
2. No scratchers.

Preflush, displacement rate, plugs, reciprocation, etc.

1. Use stab-in tool to cement through drill pipe.
2. Pump 100 cu. ft. of water and 100 cu. ft. of pre-flush ahead of cement.
3. Do not reciprocate. Do top job if top of cement settles.

Pressure testing and landing

1. Do not exceed testing pressure of 800 psi.
2. Have representative from State to witness the test.
3. [illegible]

Table 7.2 cont'd

CASING AND CEMENTING PROGNOSIS

SIZE	DEPTH	WELL
9-5/8"	2,000′	Puna-Exploration

INTERVAL	WEIGHT LB/FT	GRADE	JOINT TYPE	CALCULATED SAFETY FACTORS		
				BURST	COLL.	TENSION
0-2,000′	40.0	L-80	Buttress	2.3	3.1	High

DESIGN CONDITIONS

Surface Burst Pressure	1,500 psi		Outside mud wt. (collapse)	9.6	ppg
Inside Mud Weight (Burst)	9.6	ppg	Inside mud wt. (collapse)	0.0	ppg
Outside Mud Weight (Burst)	8.6	ppg	Form. press. grad. at shoe (collapse)	--	ppg

CEMENT PROGRAM

SLURRY DESCRIPTION AND PROPERTIES

SLURRY DESCRIPTION: Class "G" cement, 50 lb/sk spherelite, 0.5% CFR-2, 4% Gel, 0.15% HR-7, 5% Halad 22. Tail slurry: Class "G" cement, 40% Silica Four, 0.5% CFR-2. Retard as needed for BHT.

DESIRED TOP: Surface EXCESS: 100%

SLURRY VOL.- CU. FT.	960	175	
SLURRY YIELD - CU. FT./SACK	3.16	1.62	
SLURRY DENSITY - PPG	11.10	15.40	
THICKENING TIME	2-3 hrs.	2-3 hrs.	
COMPRESSIVE STRENGTH - PSI (HRS)	1,100 (24 hrs)	2,320 (8 hrs)	

RUNNING AND CEMENTING INSTRUCTIONS

Shoe, collars

1. Halliburton float shoe and float collar.
2. Weld bottom of collars on bottom 3 joints. Use thread lock compound on first 3 collars.

Centralizers - number, type and spacing

1. Run one centralizer above shoe, one in middle of first collar, then two on each of the next three joints, then one every other joint.

Preflush, displacement rate, plugs, reciprocation, etc.

1. Circulate with mud at least 1 bottoms-up volume.
2. Pump 100 cu. ft. of water followed by 100 cu. ft. of preflush ahead of cement.

Pressure testing and landing

1. Do not exceed testing pressure of 800 psi.
2. Have representative from State to witness the test.

Table 7.2 cont'd

CASING AND CEMENTING PROGNOSIS

SIZE	DEPTH	WELL
7-5/8"	4,000′	Puna-Exploration

INTERVAL	WEIGHT LB/FT	GRADE	JOINT TYPE	CALCULATED SAFETY FACTORS		
				BURST	COLL.	TENSION
0-4,000′	29.7	L-80	Buttress	1.87	2.4	6.0

DESIGN CONDITIONS

Surface Burst Pressure	1,500	psi	Outside mud wt. (collapse)	9.6	ppg
Inside Mud Weight (Burst)	9.6	ppg	Inside mud wt. (collapse)	0.0	ppg
Outside Mud Weight (Burst)	8.6	ppg	Form. press. grad. at shoe (collapse)	--	ppg

CEMENT PROGRAM

SLURRY DESCRIPTION AND PROPERTIES

SLURRY DESCRIPTION: Class "G" cement, 40% Silica Flour, 0.5% CFR-2, 3% Gel.

Retard as needed for BHT.

DESIRED TOP: Surface EXCESS: 100%

SLURRY VOL.- CU. FT.	742	--	
SLURRY YIELD - CU. FT./SACK	1.53	--	
SLURRY DENSITY - PPG	16.0	--	
THICKENING TIME	2-3 hrs.	--	
COMPRESSIVE STRENGTH - PSI (HRS)	2,320 (8 hrs)	--	

RUNNING AND CEMENTING INSTRUCTIONS

Shoe, collars

1. Equip casing with 7" float shoe with liner tie-back guide on bottom joint.
2. Use 7" float collar above first joint.

Centralizers - number, type and spacing

1. Run one centralizer above shoe, one in middle of first joint, then every third joint up to 100 ft. from surface.
2. Chain down casing prior to cementing.

Preflush, displacement rate, plugs, reciprocation, etc.

1. Circulate with 100 cu. ft. of water ahead of cement.
2. Displace cement with mud.

Pressure testing and landing

1. Do not exceed 1,500 psi when testing BOPs.
2. Test casing and liner lap to 1,500 psi before drilling cement.

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Table 7.3 Larger Historic Earthquakes Felt (But Not Necessarily Located) in the KERZ ($M \geq 6$, $I \geq VII$)

Year	I	M	Comment
1886	X	>7	Very destructive over most of Hawaii, felt on Oahu and Kauai. 10-foot tsunami.
1919	VII	--	Chimneys down at Kilauea.
1941	VII	--	Mauna Loa area (near KERZ).
1951	VII	6.5	Slight damage in Hilo; small landslides triggered.
1955	VII	--	Waterlines broken.
1975	VIII	7.2	Located on Hilina Fault; south of KERZ; largest earthquake since 1868; 20-foot tsunami; local but severe damage to structures.

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FIGURES

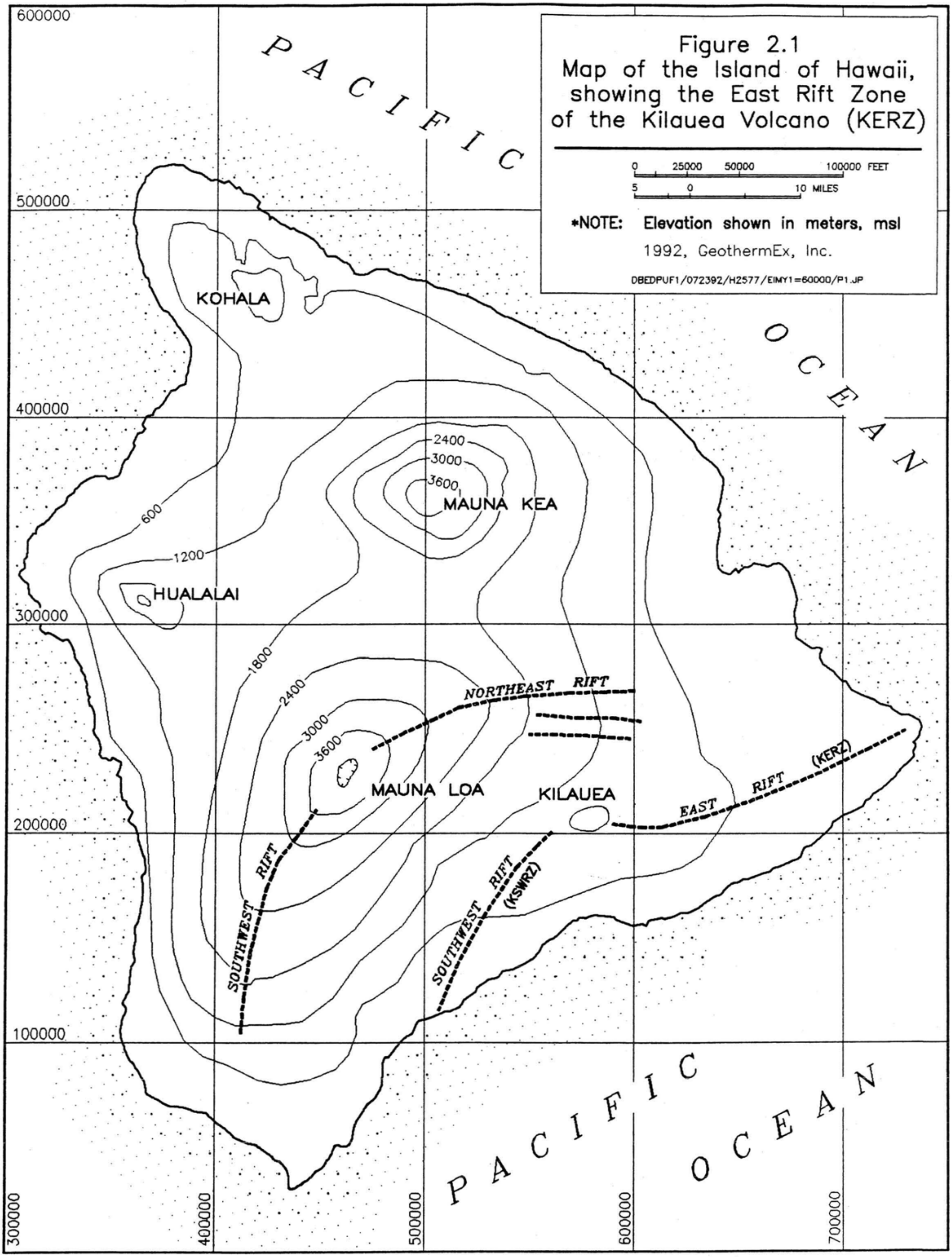


Figure 2.1
Map of the Island of Hawaii, showing the East Rift Zone of the Kilauea Volcano (KERZ)

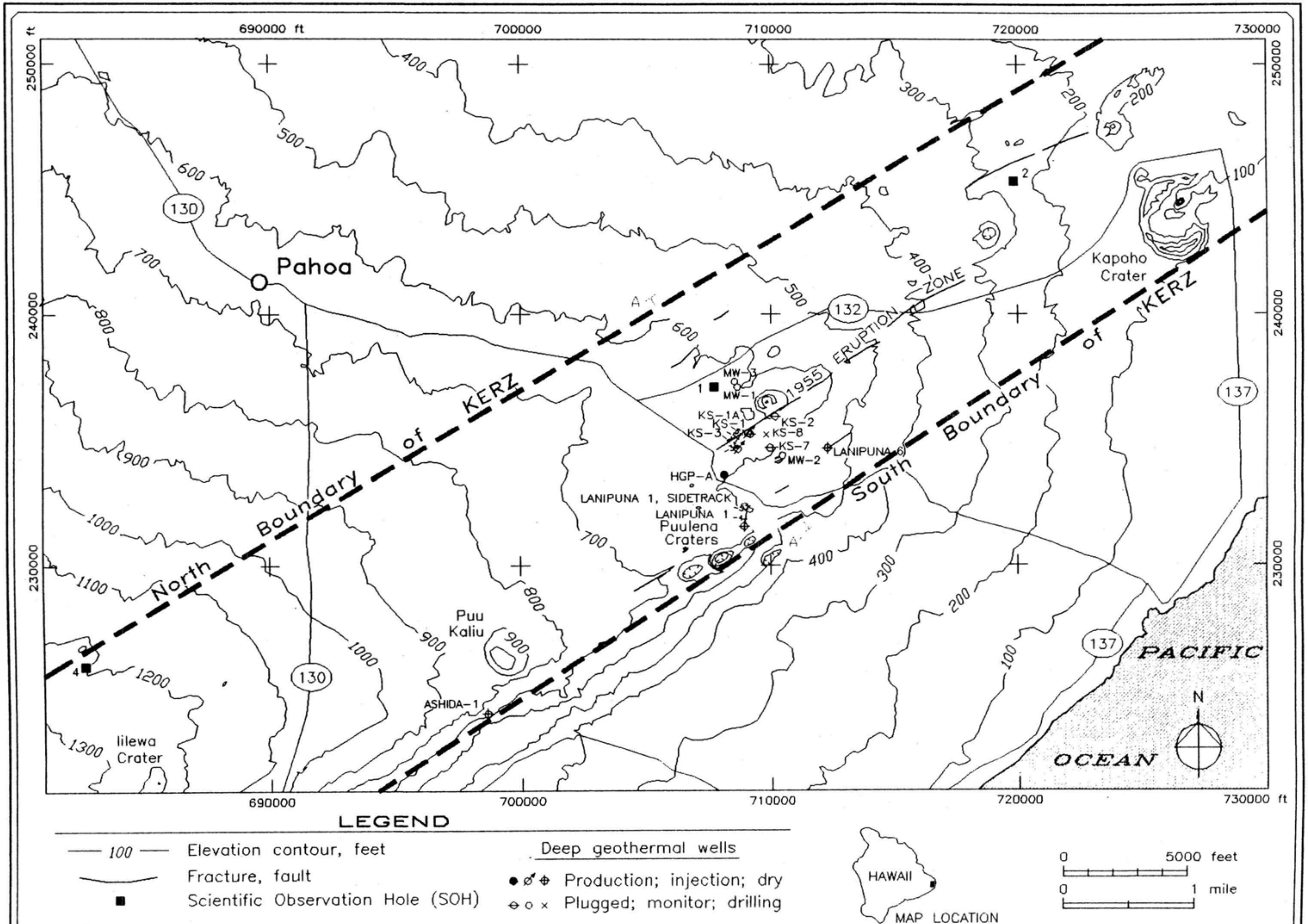


Figure 3.1: Regional map of Puna area of KERZ, showing geologic features and well locations.

1992, GeothermEx, Inc.
DBPUF31/072392/H4683/EIMN1=5280/HAWAII.JP

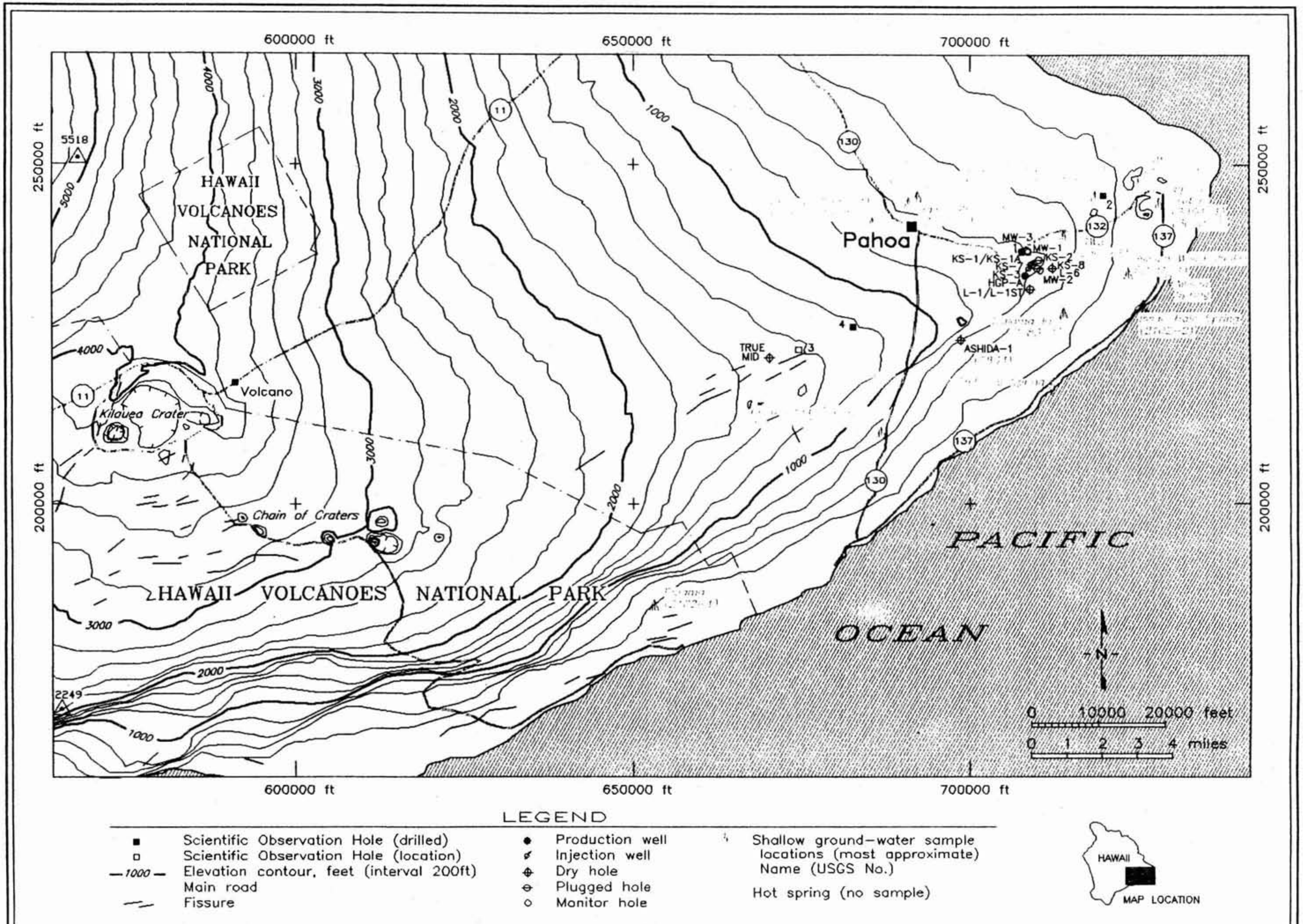


Figure 3.2: Water sample locations, KERZ, Hawaii

1992, GeothermEx, Inc. DBPUWSAM/072392/H4620/EMN1=20000/WSAM.JP

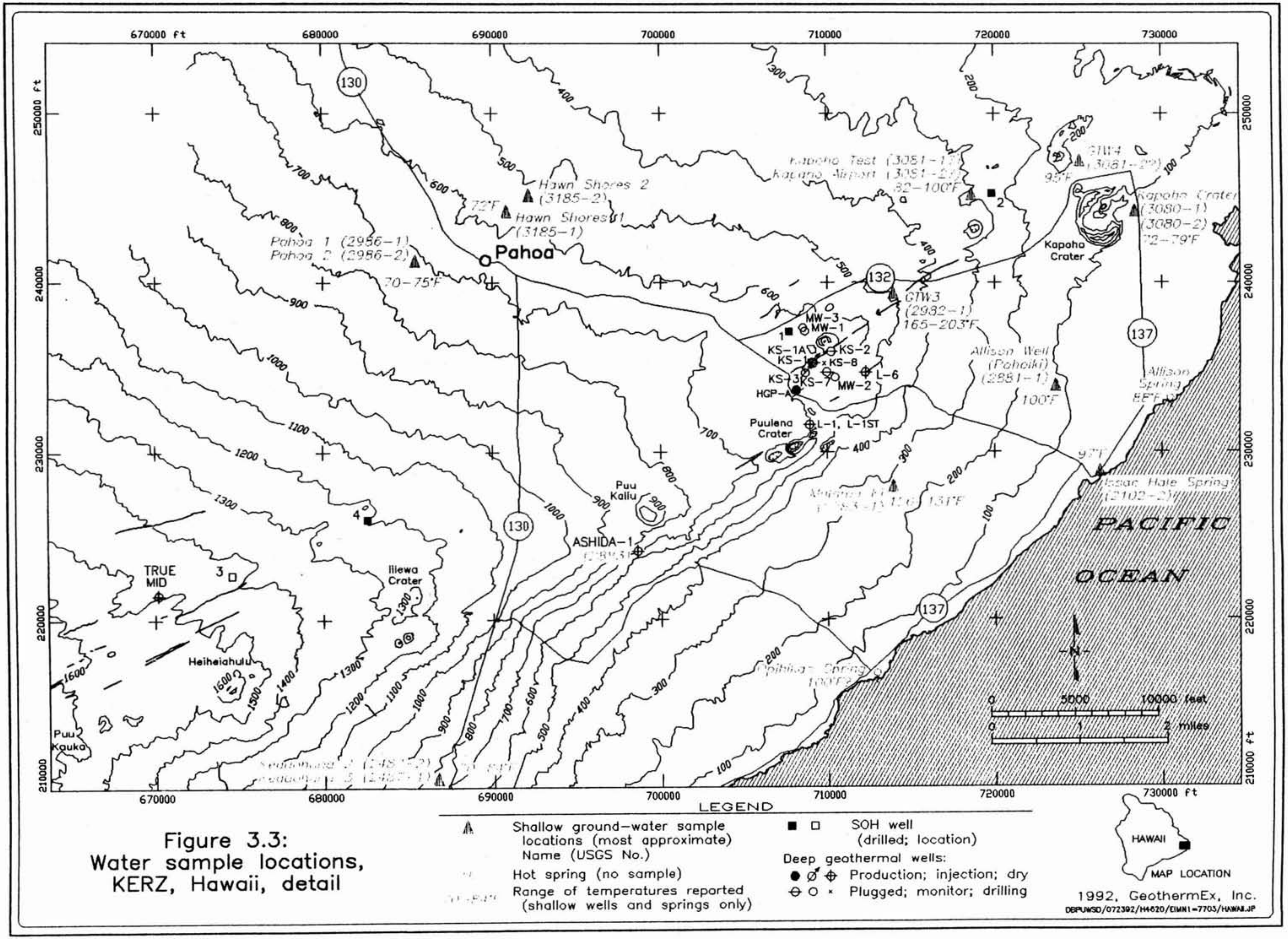


Figure 3.3: Water sample locations, KERZ, Hawaii, detail

Note: all data represent samples as collected. Thermal well samples not corrected for steam loss. Temperatures of KS-1, KS-1A and KS-2 represent reported temperature of sample 'from top of dike-impounded water' (Iovanetti, 1990).

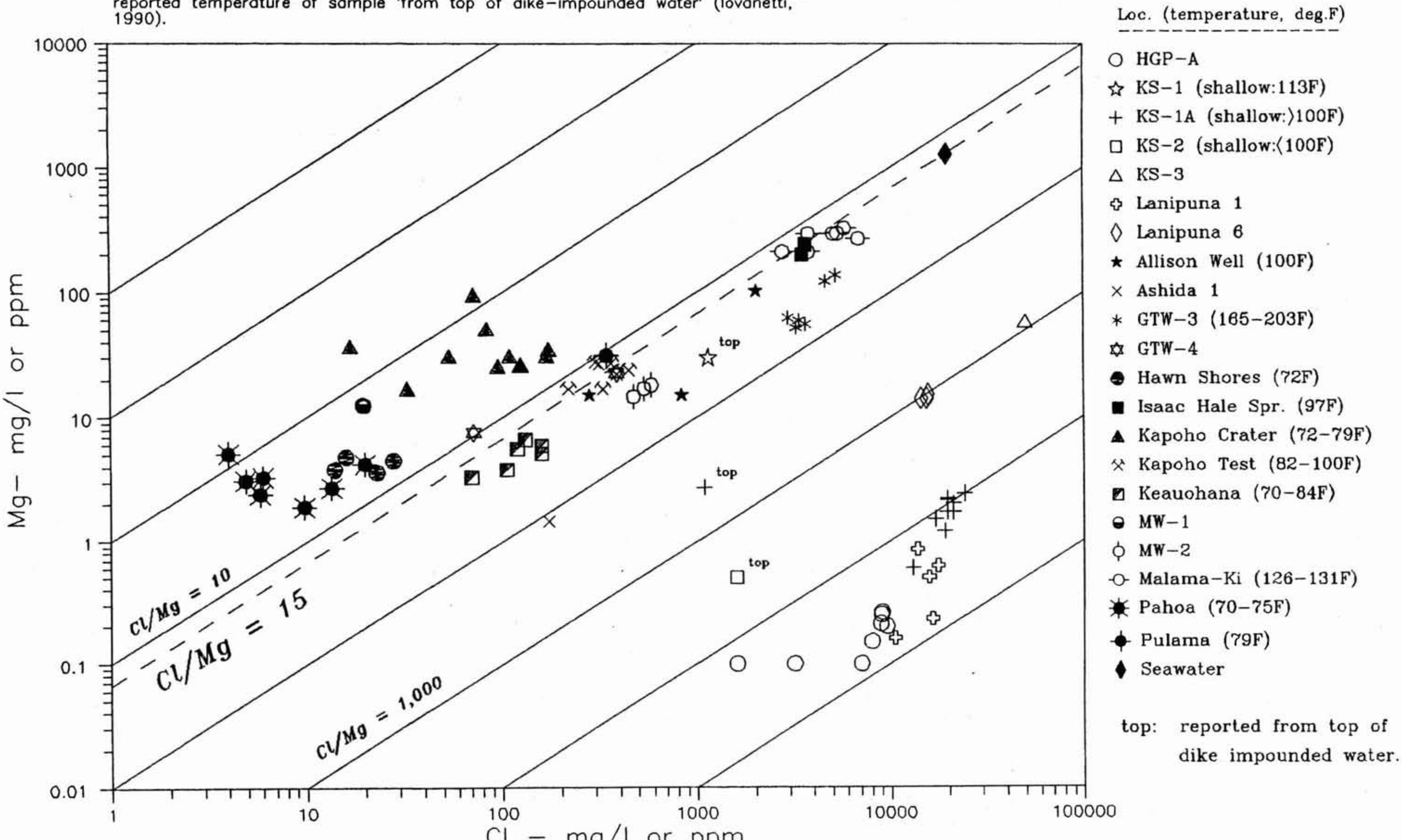


Figure 3.4 : Mg vs. Cl in waters of lower KERZ

GeothermEx,Inc.- K1778 - 920708

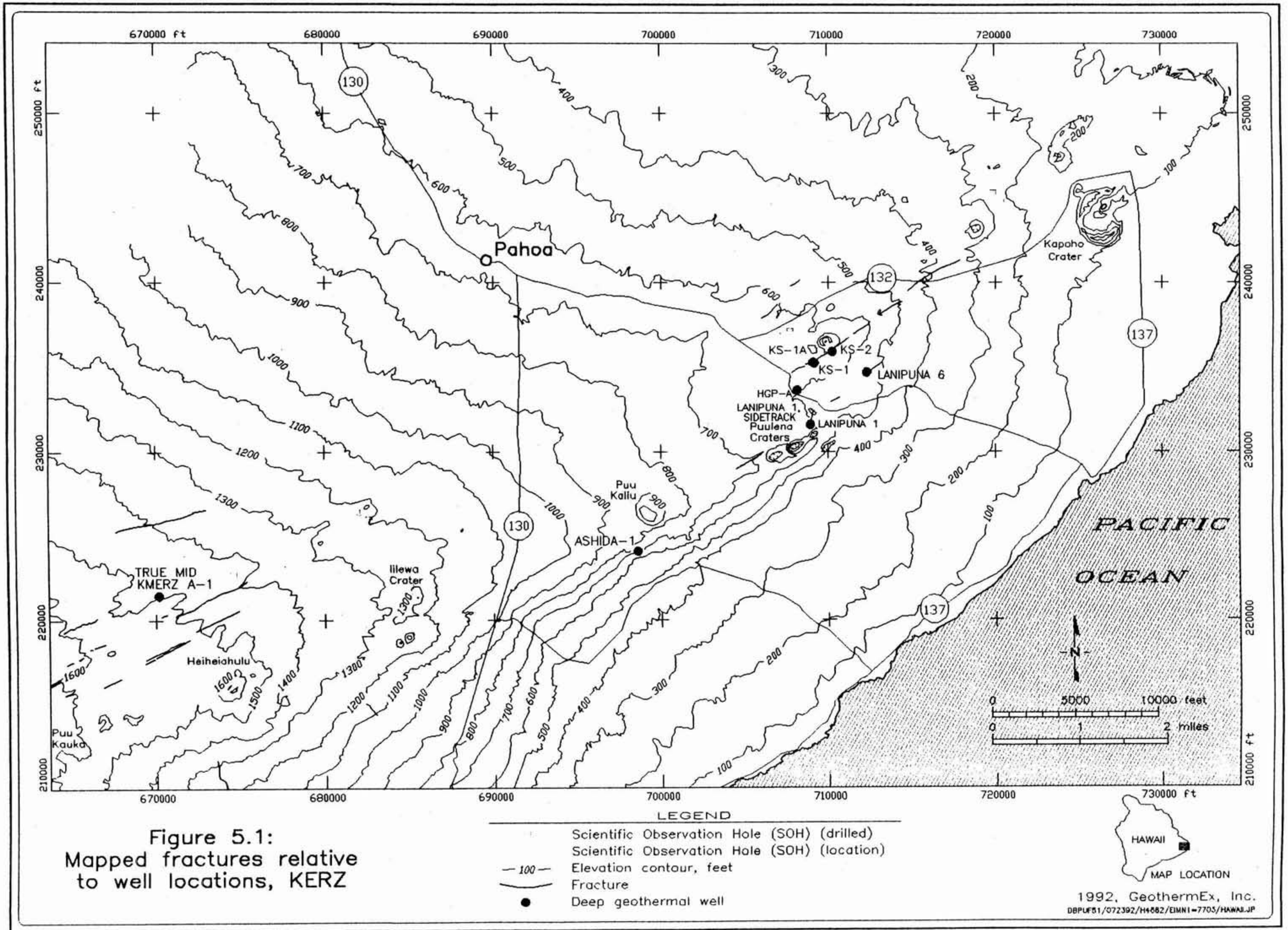


Figure 5.1:
Mapped fractures relative to well locations, KERZ

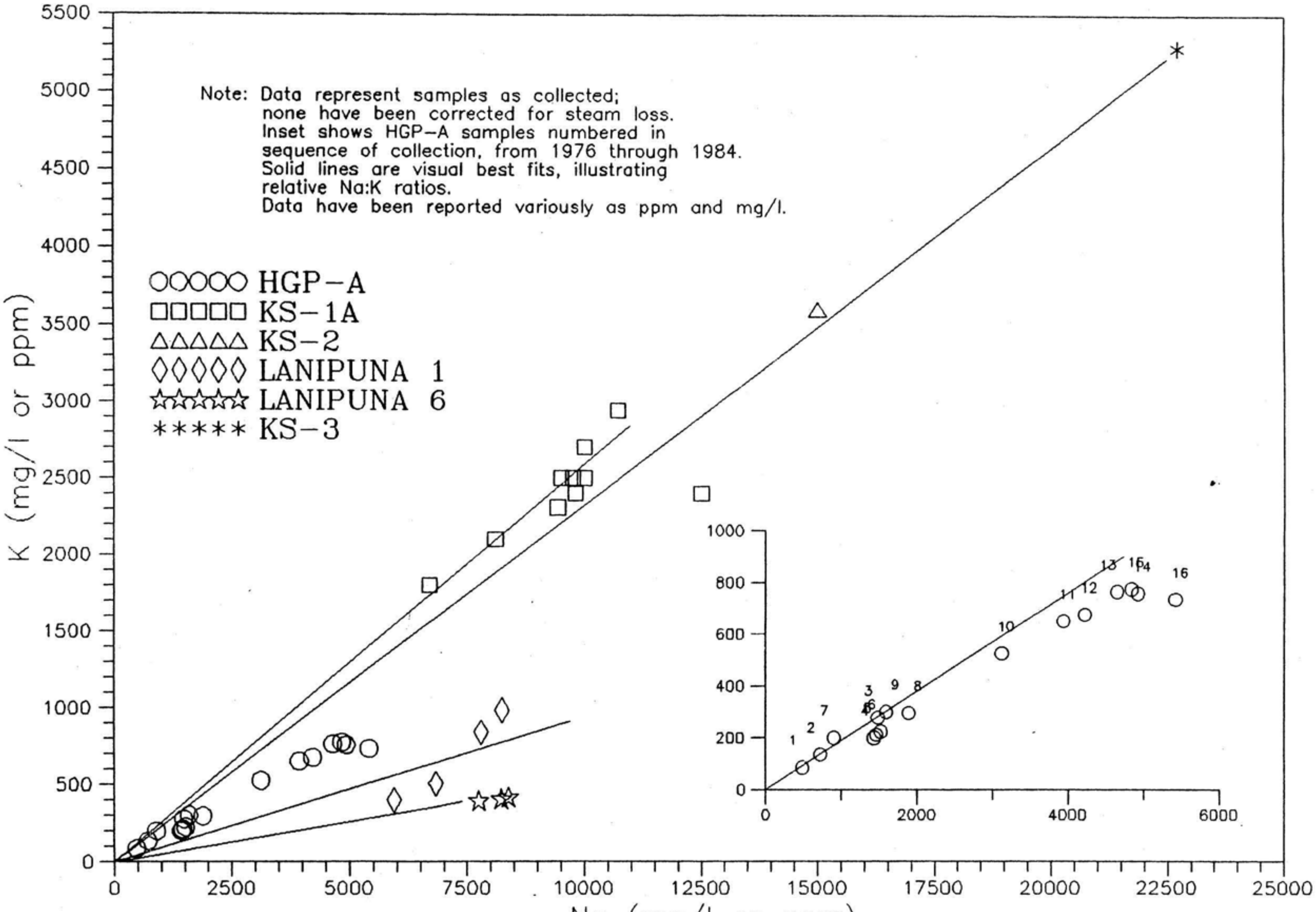


Figure 5.2 : Na vs. K in waters of KERZ geothermal wells

GeothermEx,Inc.– K1043 920717

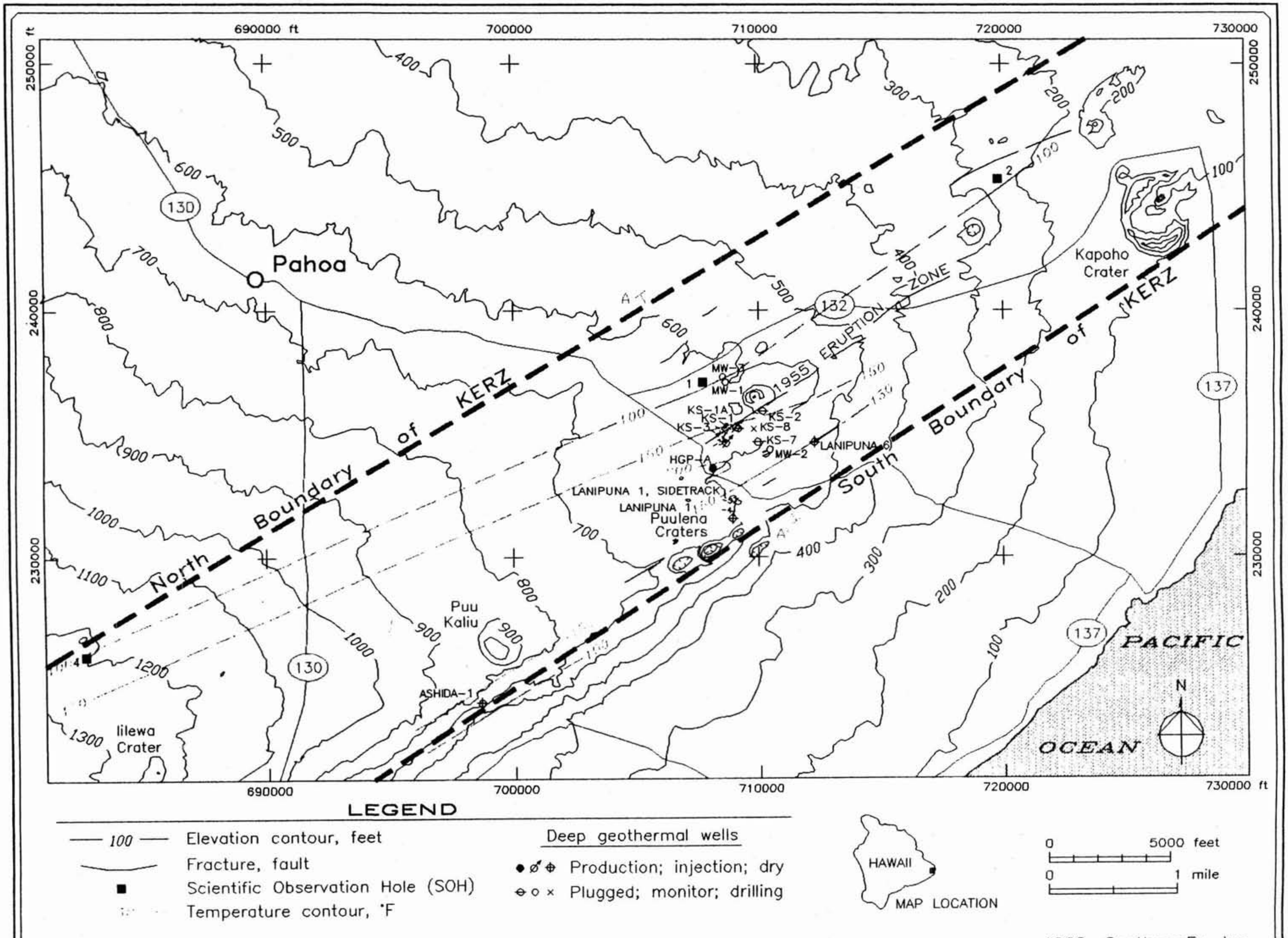


Figure 5.3: Temperature distribution at −1,000 feet, msl

1992, GeothermEx, Inc.
DBPUTM1/072392/H4685/EIMN1=5280/HAWAII.JP

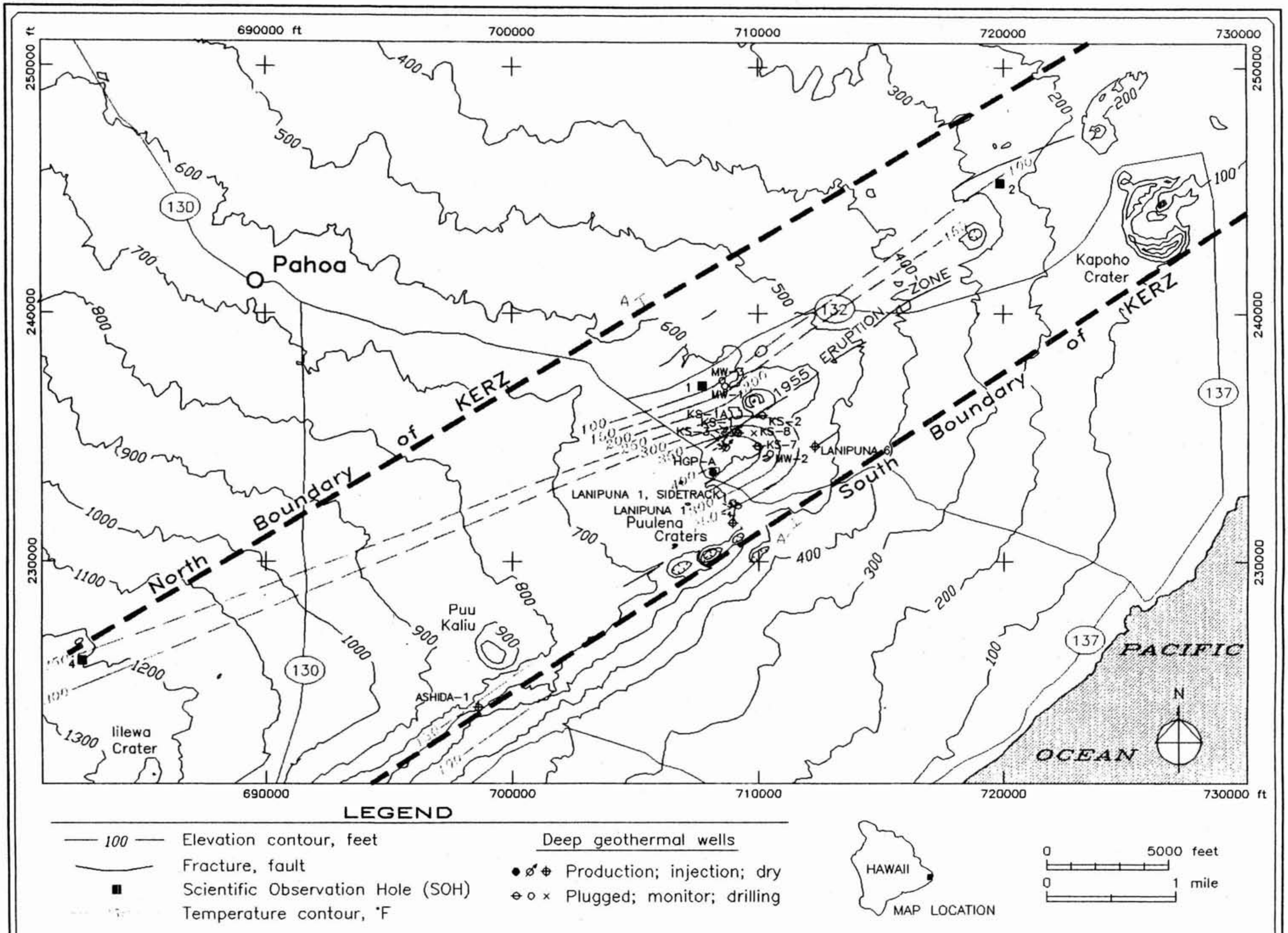


Figure 5.4: Temperature distribution at −2,000 feet, msl

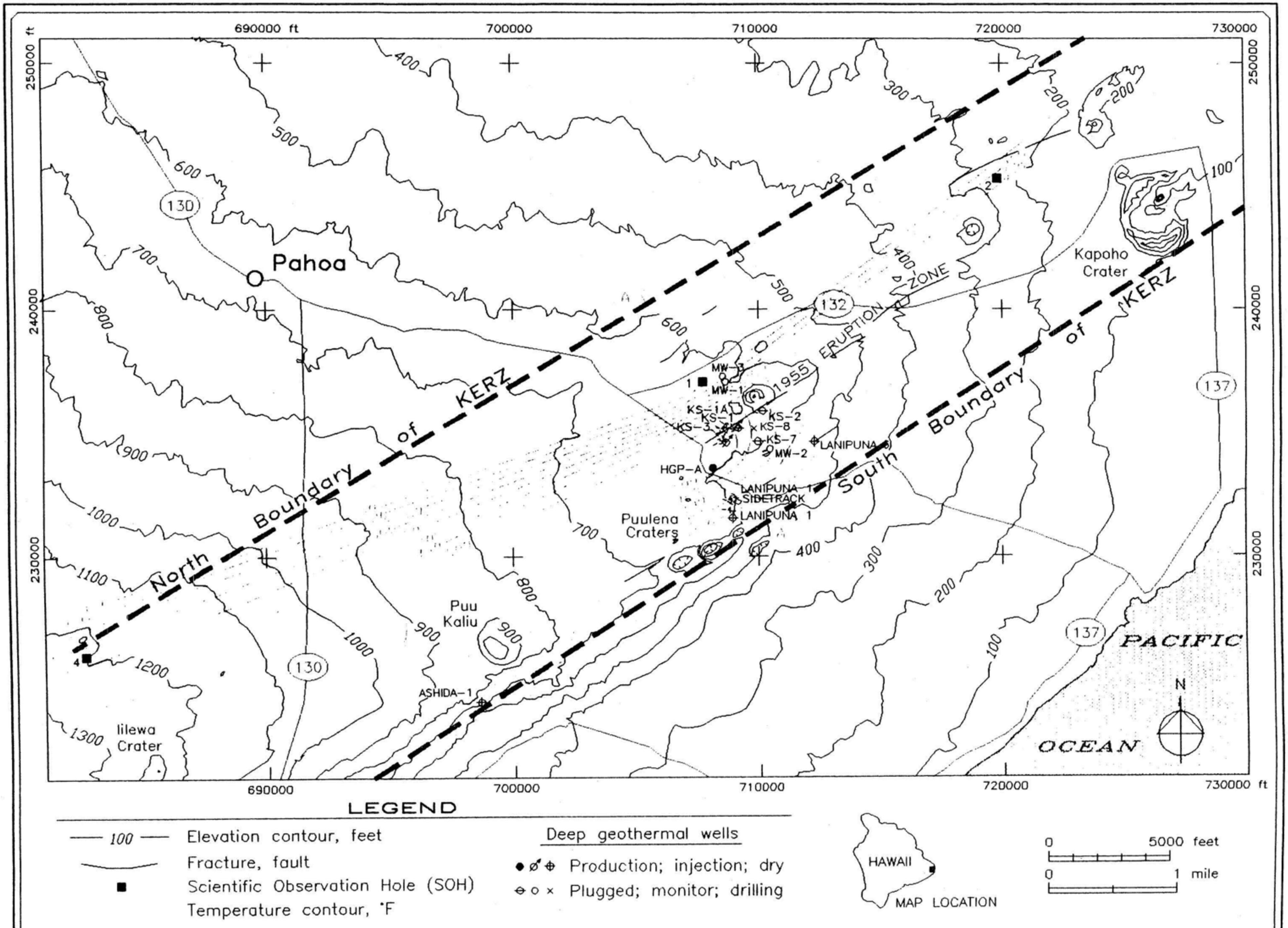


Figure 5.5: Temperature distribution at −3,000 feet, msl

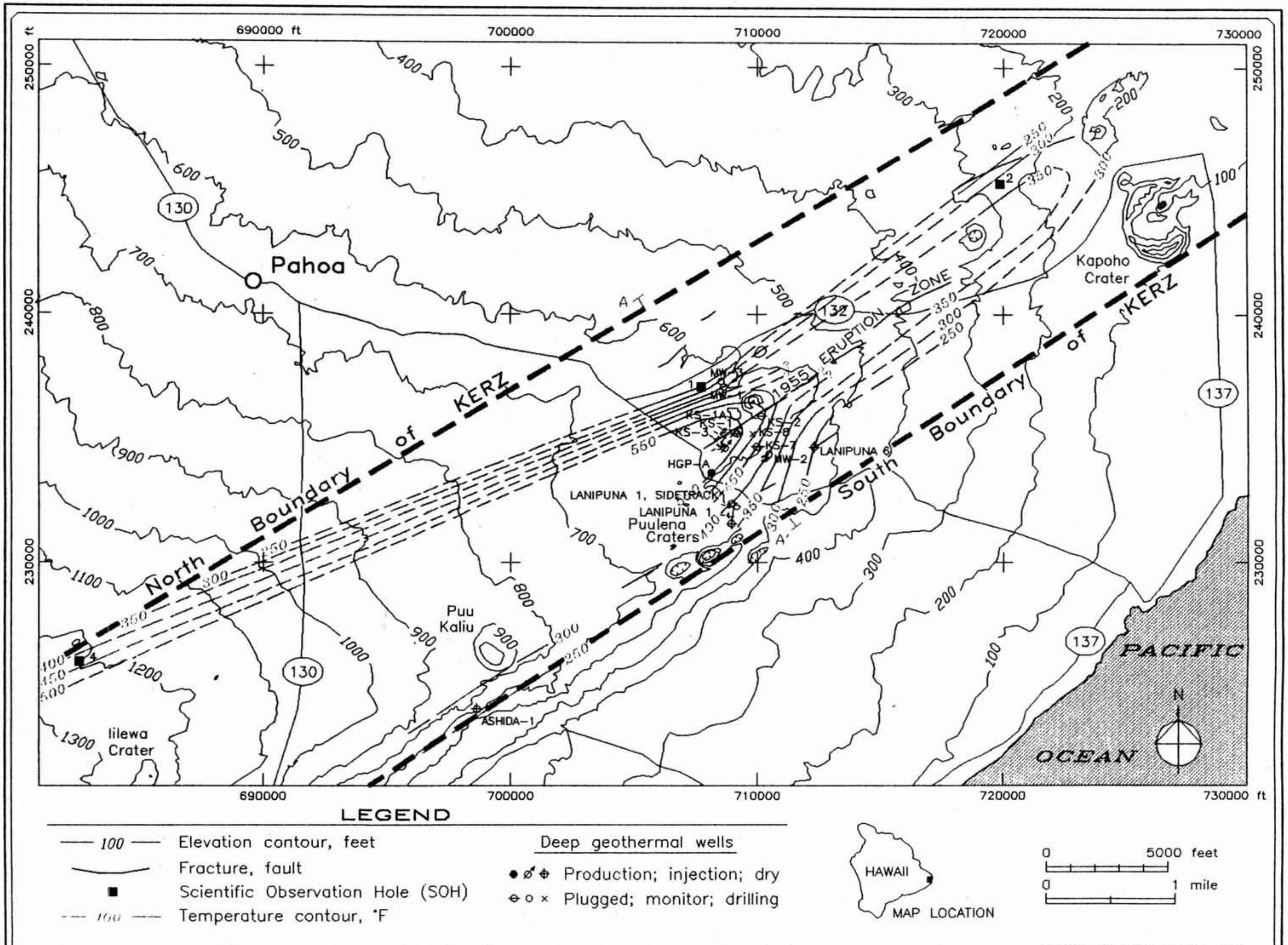


Figure 5.6: Temperature distribution at −4,000 feet, msl

1992, GeothermEx, Inc.
DBPUTM4/093092/H4689/EIMN1-5280/HAWAII.JP

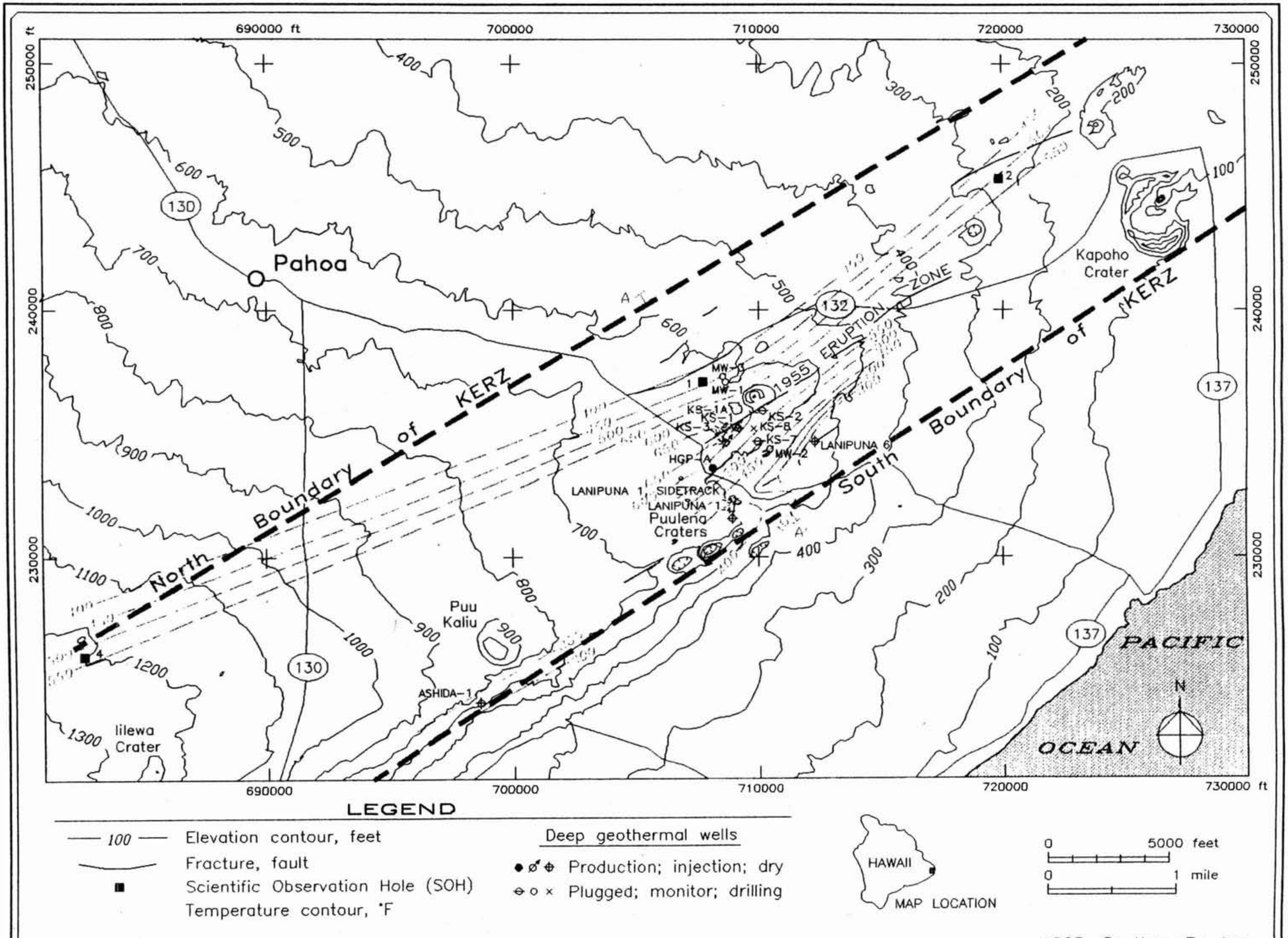


Figure 5.7: Temperature distribution at −5,000 feet, msl

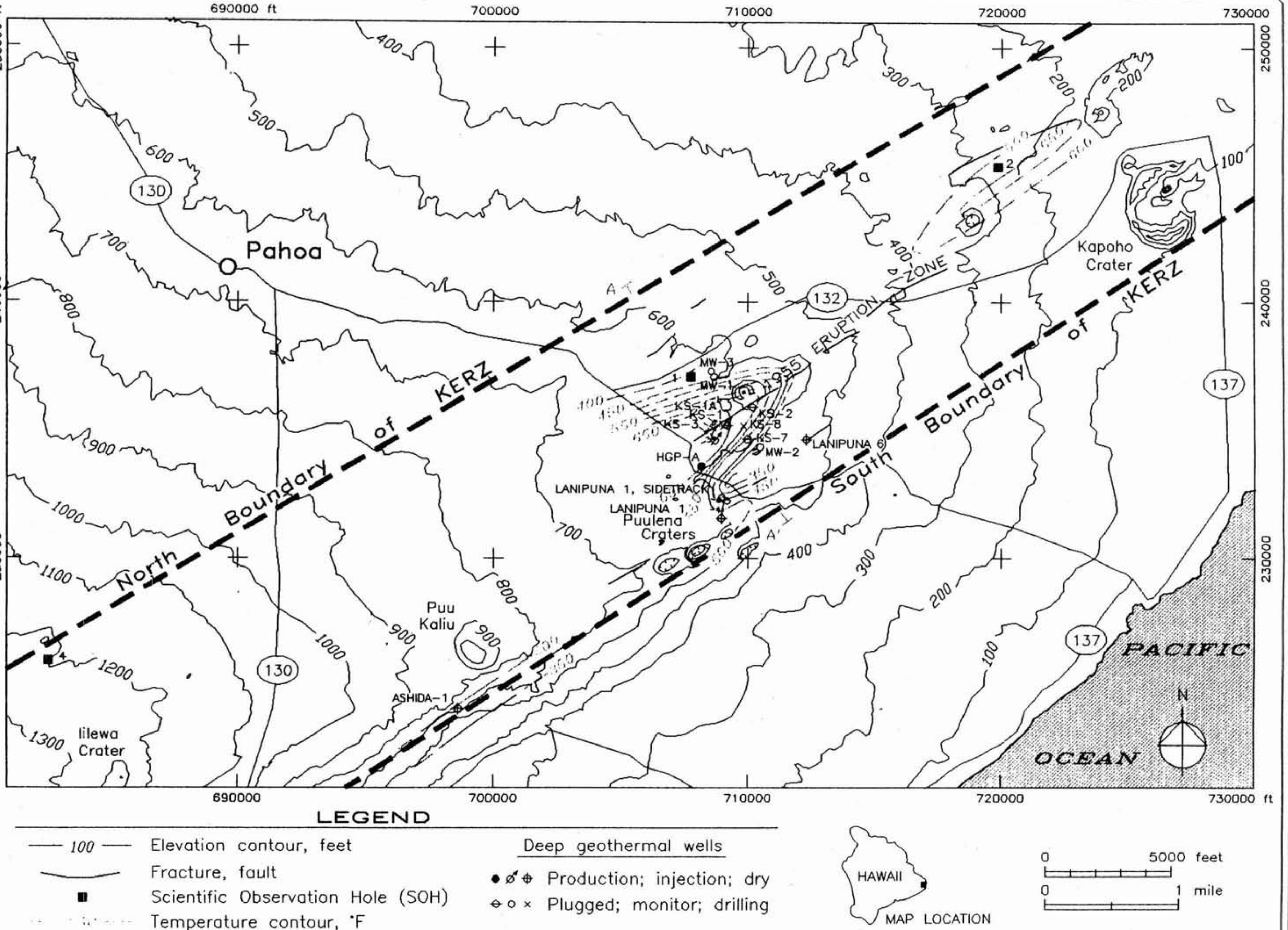


Figure 5.8: Temperature distribution at −6,000 feet, msl

1992, GeothermEx, Inc.
DBPUTM6/093092/H4689/EIMN1=5280/HAWAII.JP

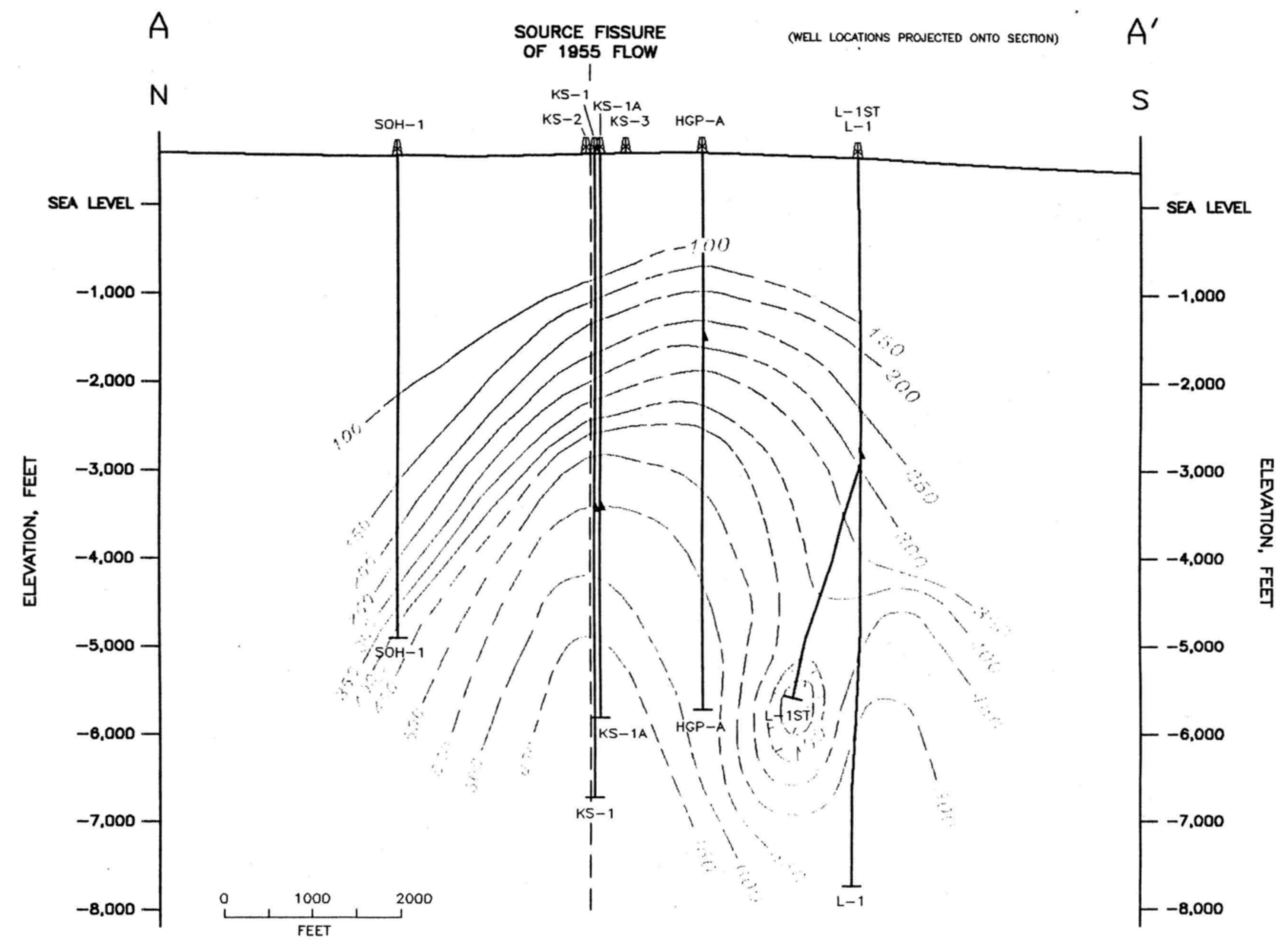
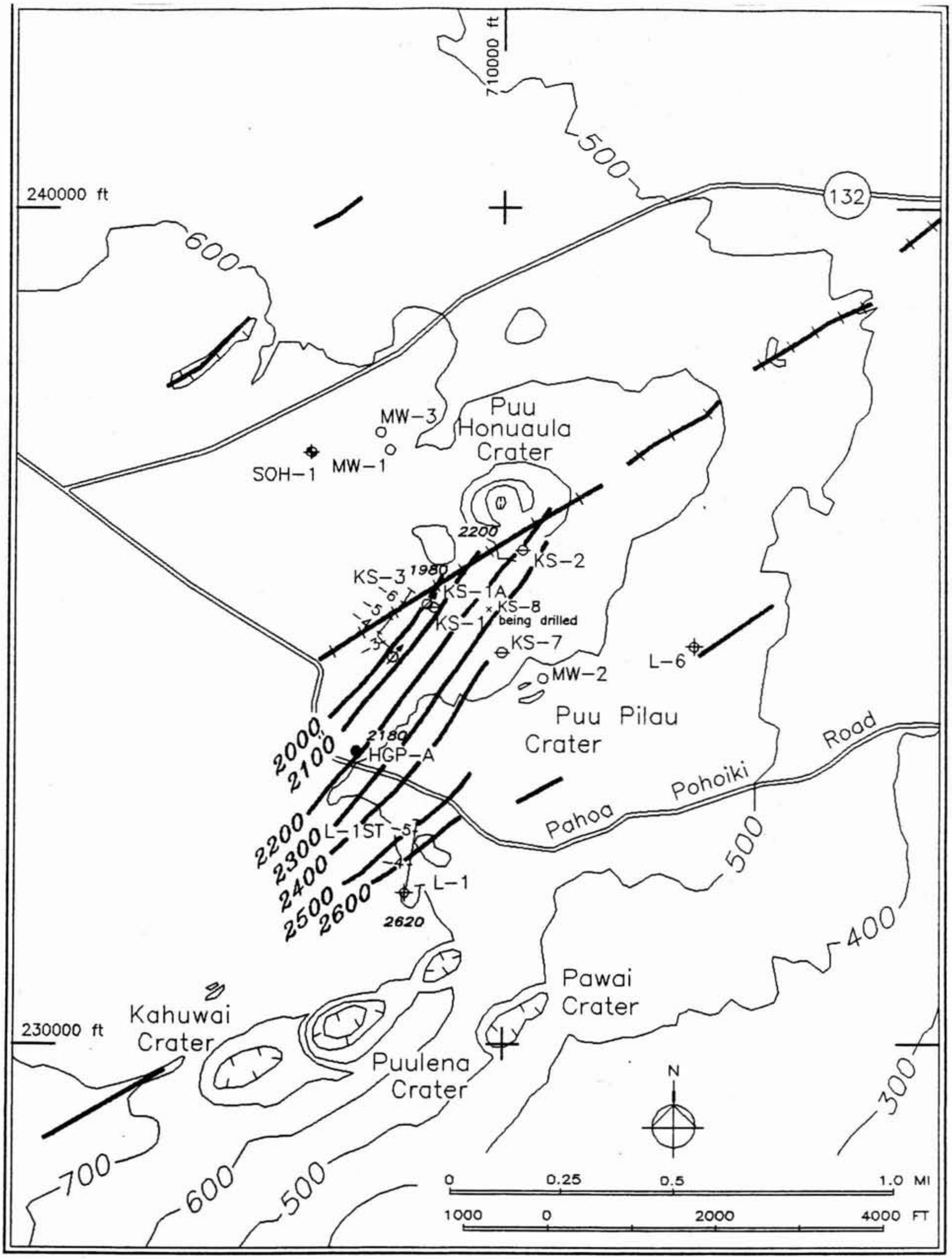


Figure 5.9: Temperature cross-section A-A'

1992, GeothermEx, Inc. PUNAF59/093092/H2577/EMN1=1666.666/HAWAII.JP



LEGEND

2500 Pressure at −5,000 feet (msl), psig

● Production well

Injection well

Dry hole

o Monitor hole

Plugged hole

Core hole

Fissure (1955 eruption zone)

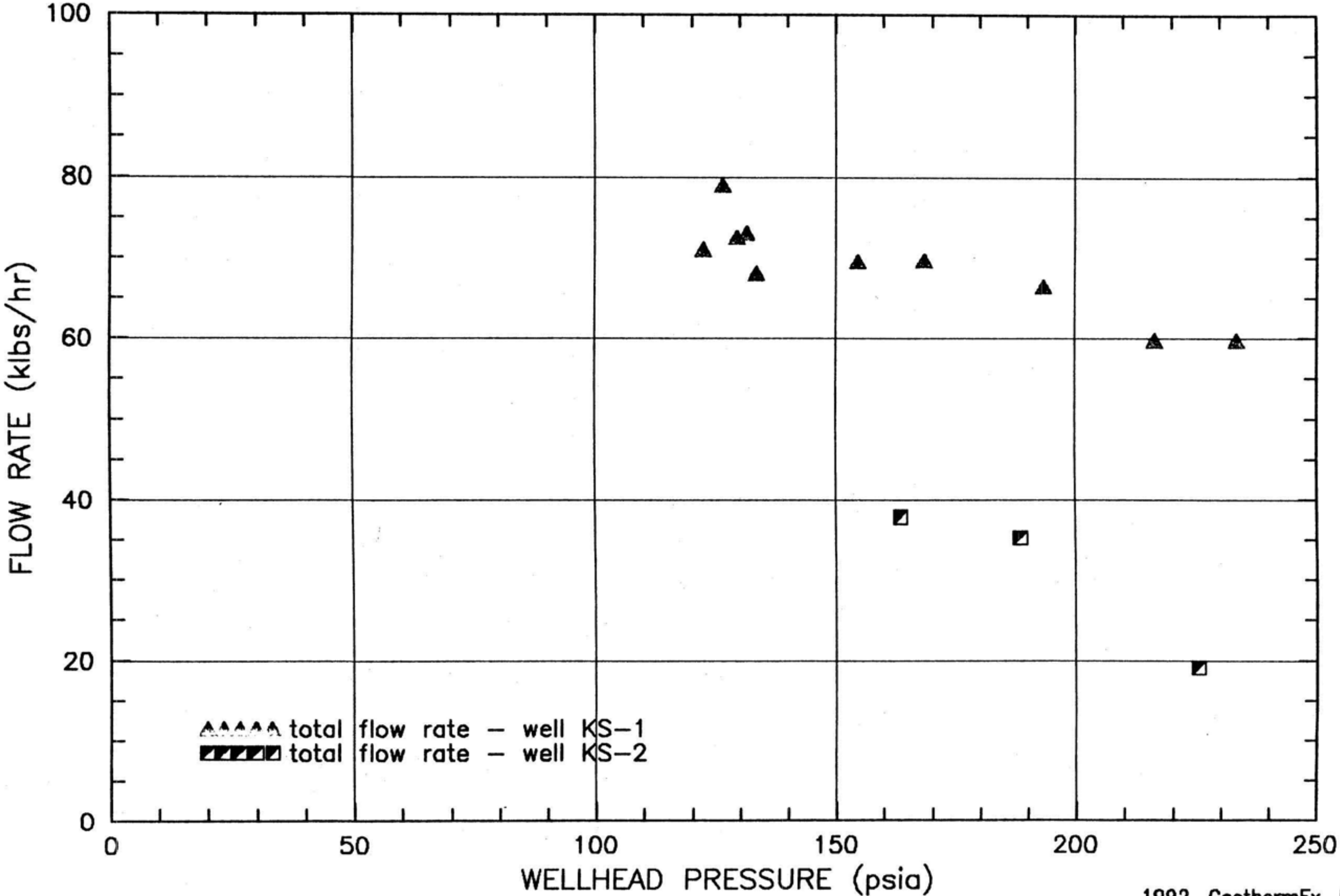
Fracture

—600— Elevation contour, feet

Figure 5.10 : Pressure distribution at −5,000 feet, msl.

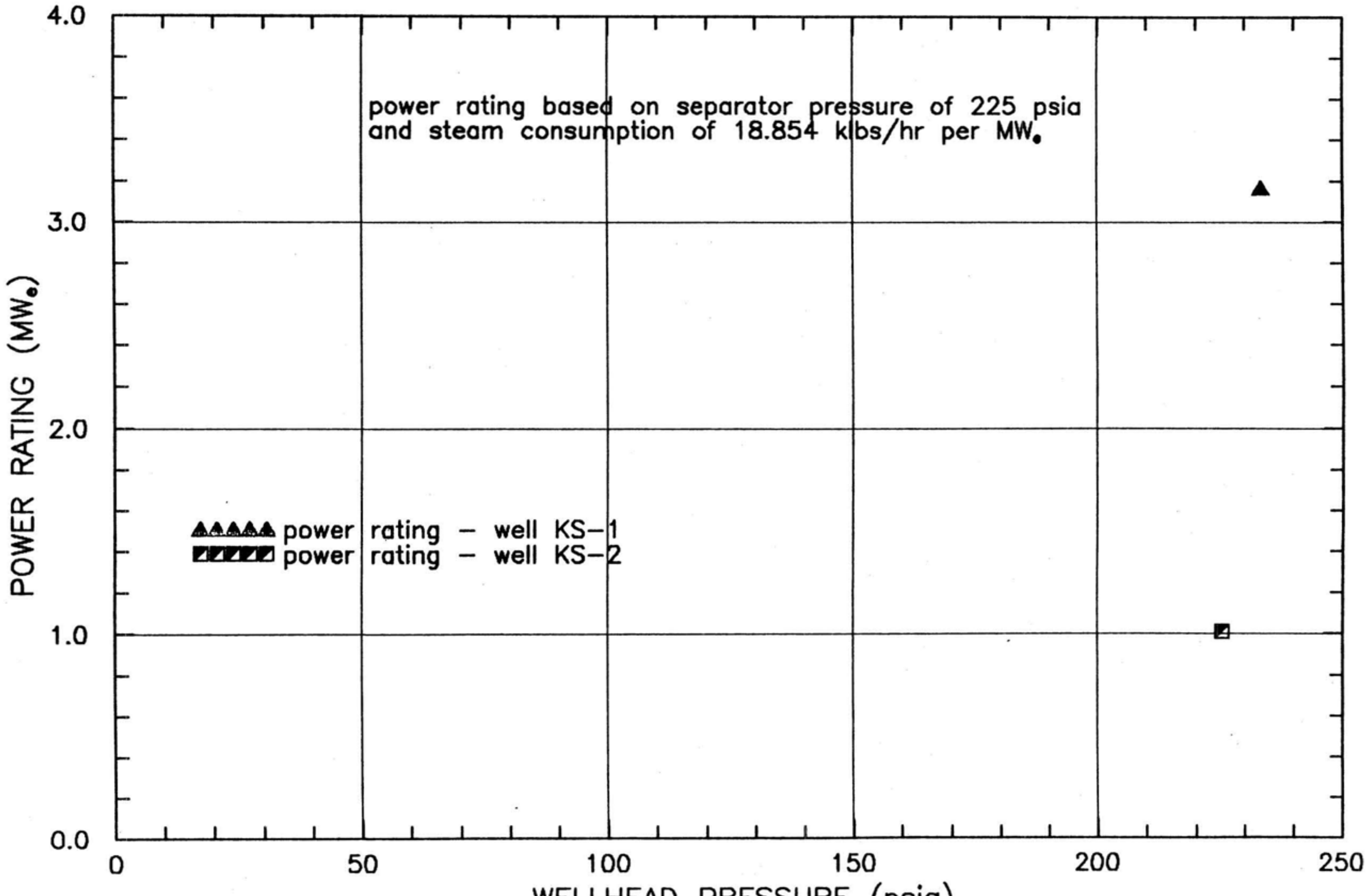
1992, GeothermEx, Inc. PUNAF510/093092/H2577/EIMY1=1800/HAWAII.JP

Figure 6.1: FLOW RATE vs WELLHEAD PRESSURE, WELLS KS-1 and KS-2



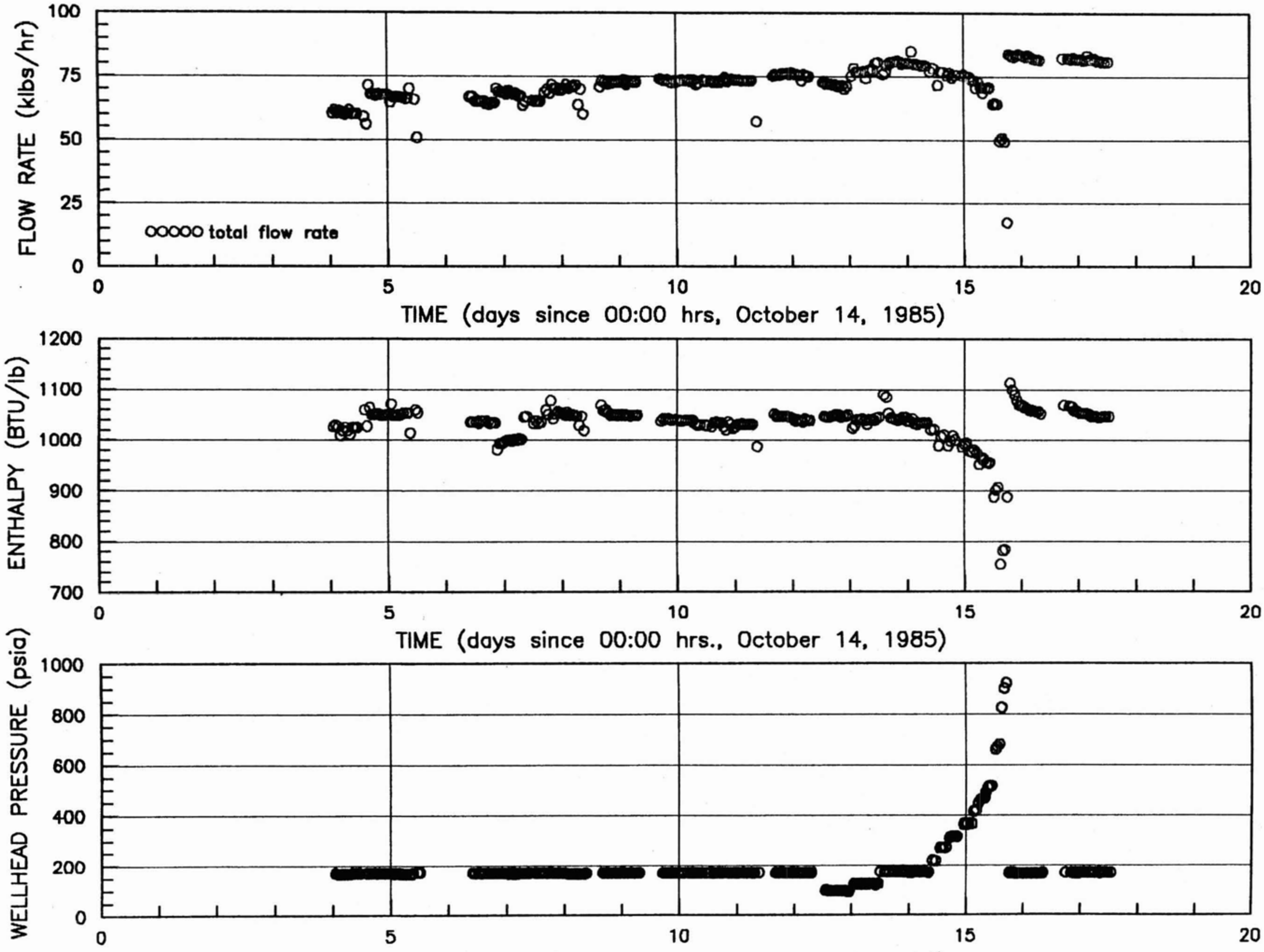
1992, GeothermEx, Inc.

Figure 6.2: POWER RATING vs WELLHEAD PRESSURE, WELLS KS-1 and KS-2



1992, GeothermEx, Inc.

Figure 6.3: TOTAL FLOW RATE, ENTHALPY and WELLHEAD PRESSURE vs TIME, WELL KS-1A



1992, GeothermEx, Inc.

Figure 6.4: FLOW RATE vs WELLHEAD PRESSURE, WELL KS-1A

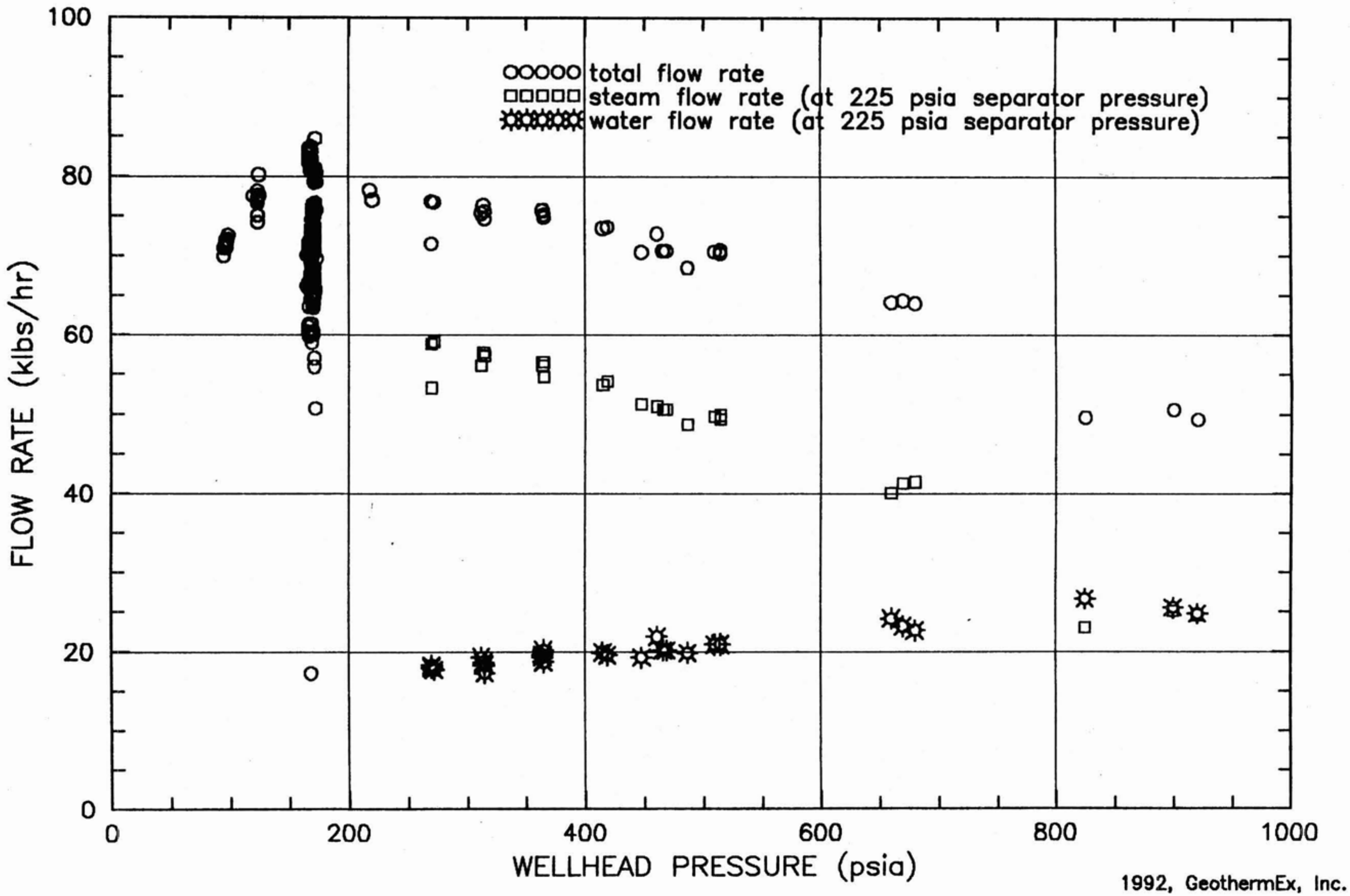
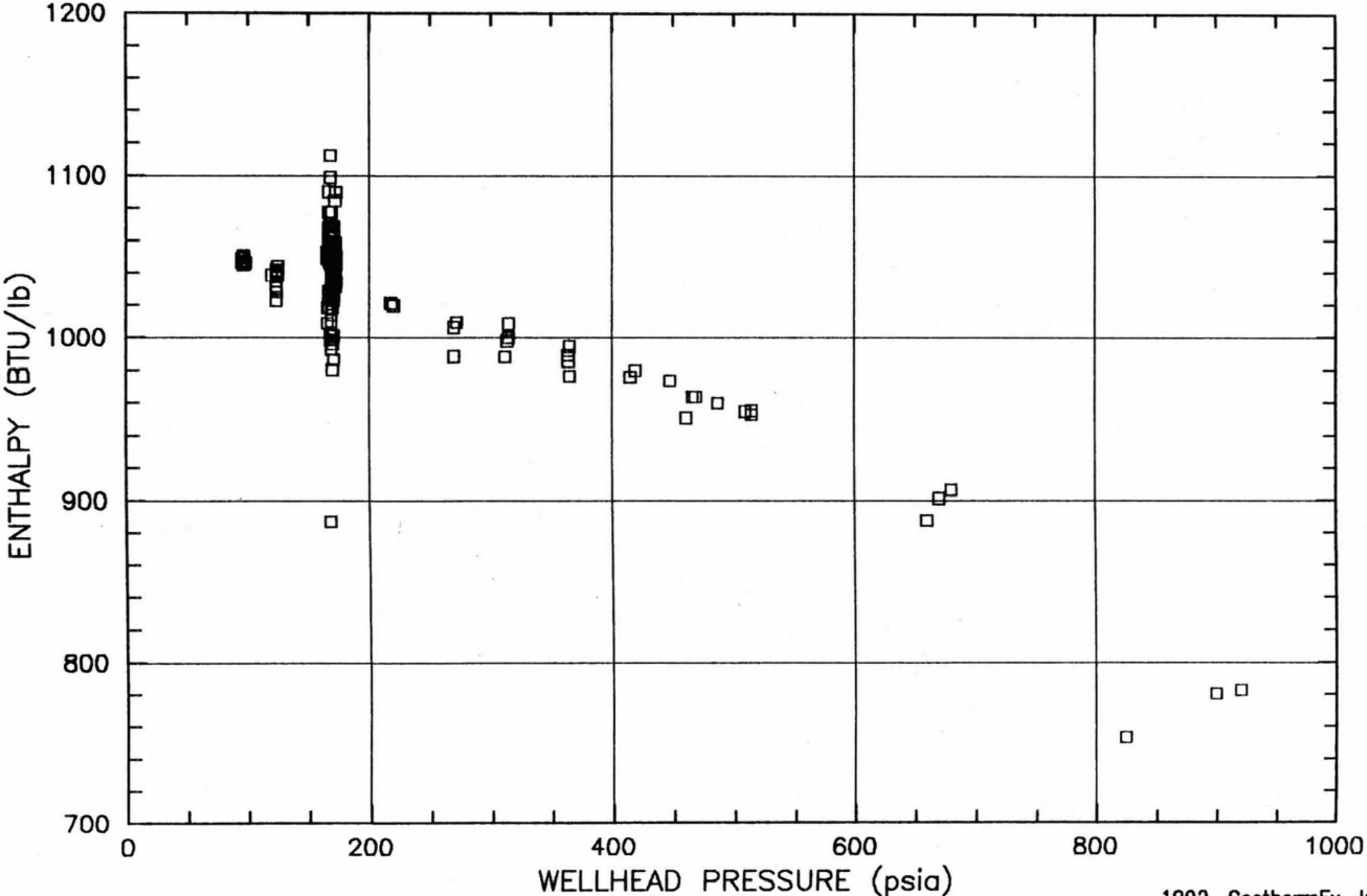


Figure 6.5: ENTHALPY vs WELLHEAD PRESSURE, WELL KS-1A



1992, GeothermEx, Inc.

Figure 6.6: POWER RATING vs WELLHEAD PRESSURE, WELL KS-1A

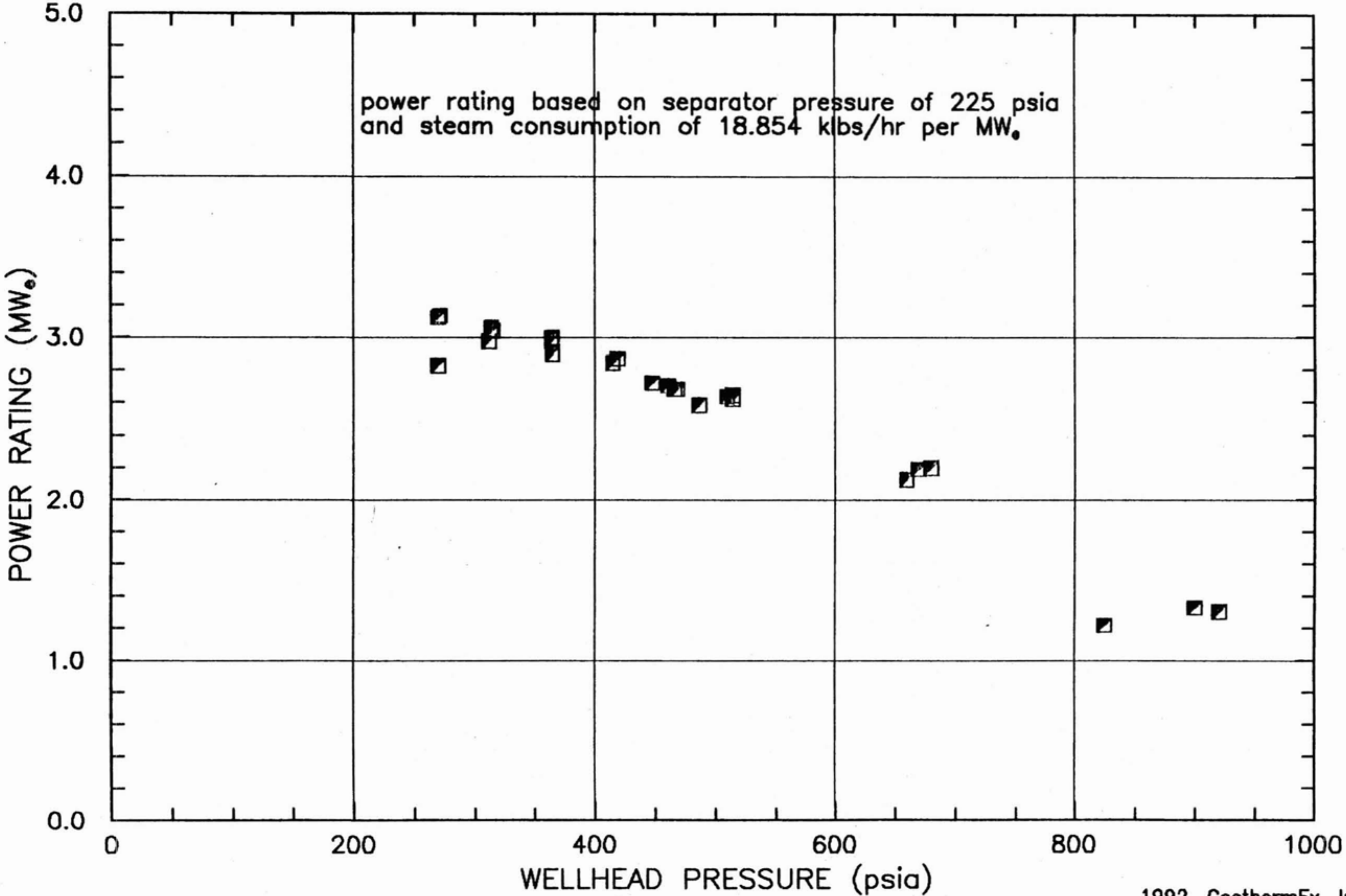
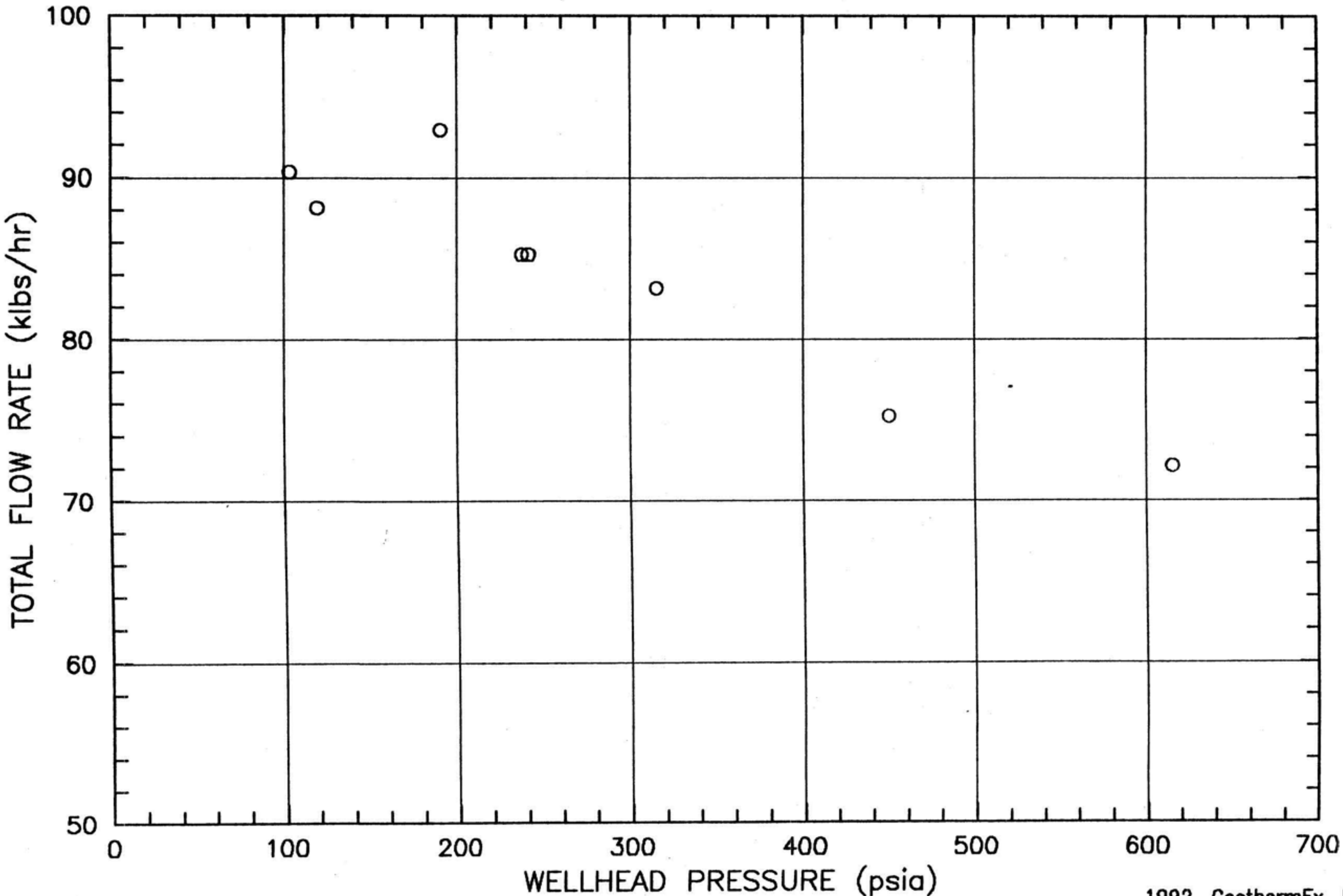
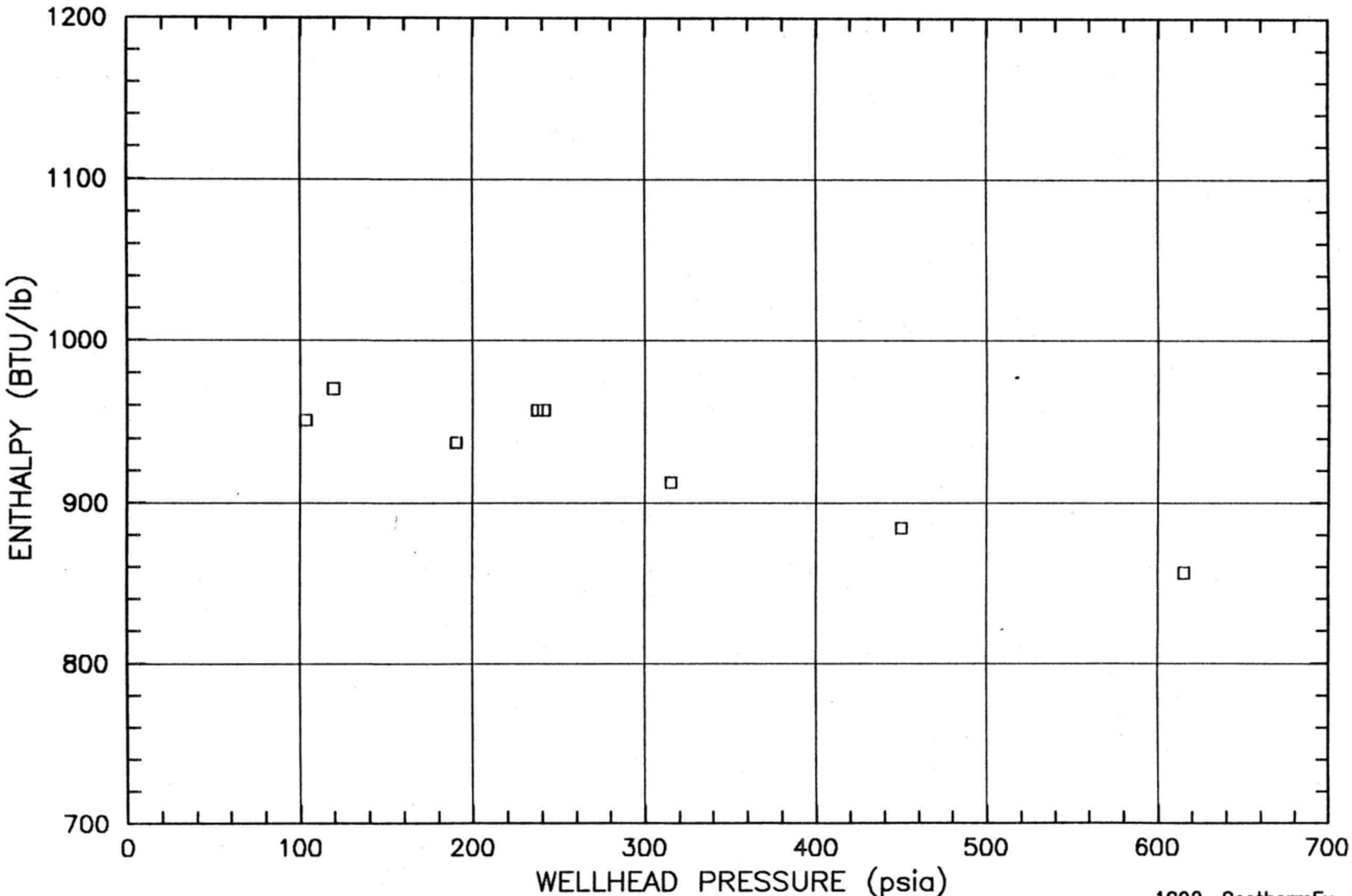


Figure 6.7: FLOW RATE vs WELLHEAD PRESSURE, WELL KS-3



1992, GeothermEx, Inc.

Figure 6.8: ENTHALPY vs WELLHEAD PRESSURE, WELL KS-3



1992, GeothermEx, Inc.

Figure 6.9: POWER RATING vs WELLHEAD PRESSURE, WELL KS-3

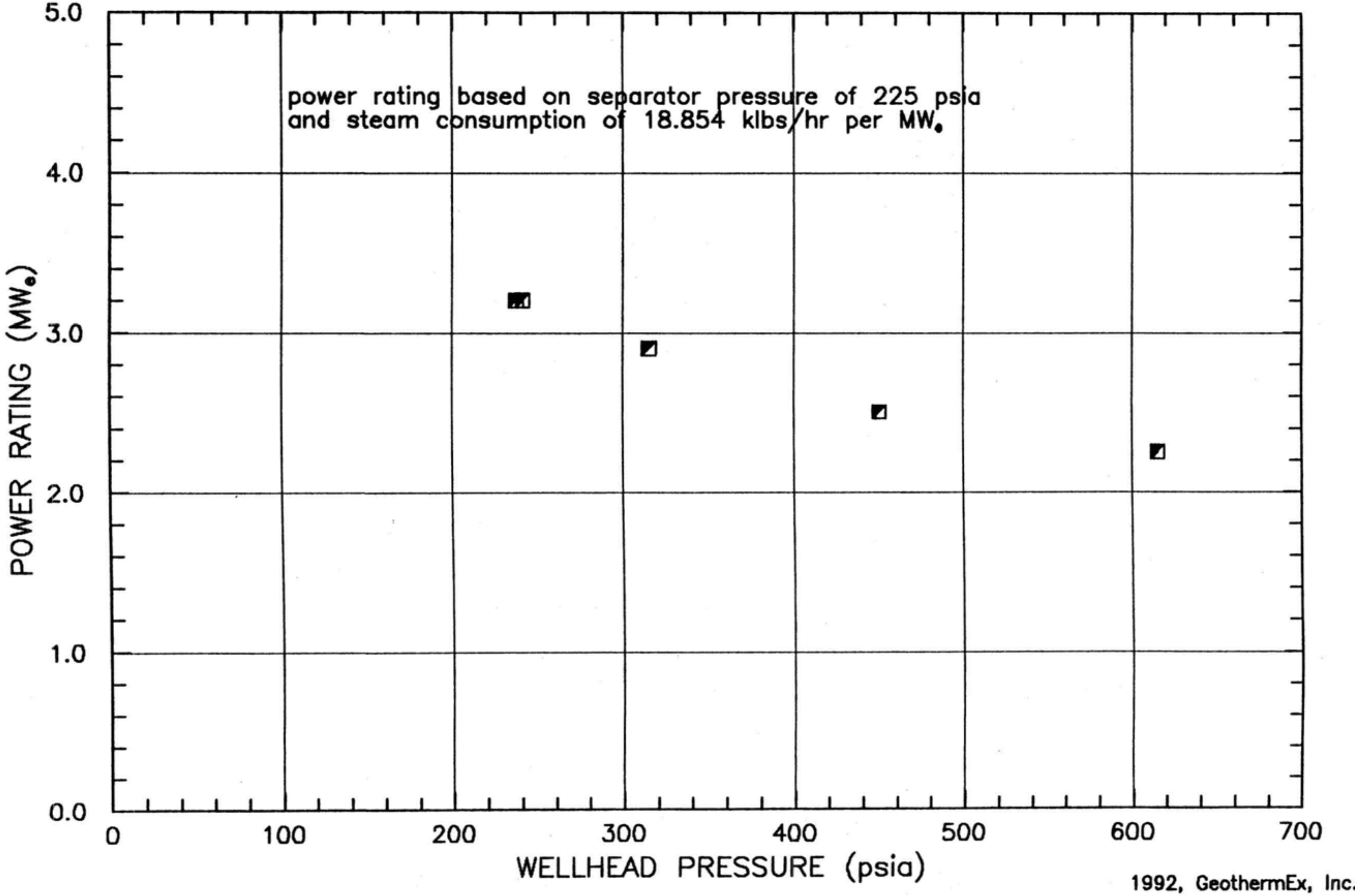
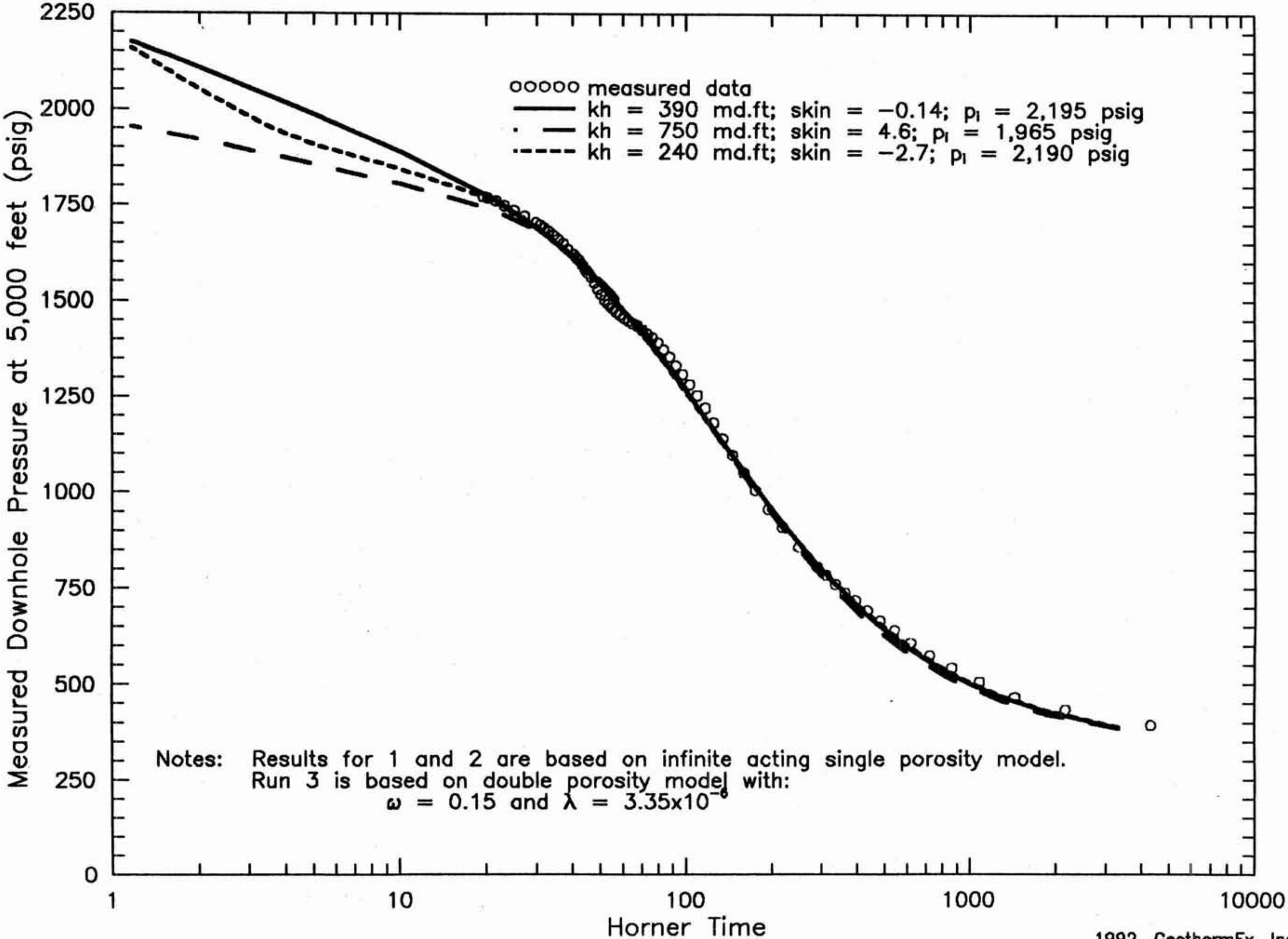
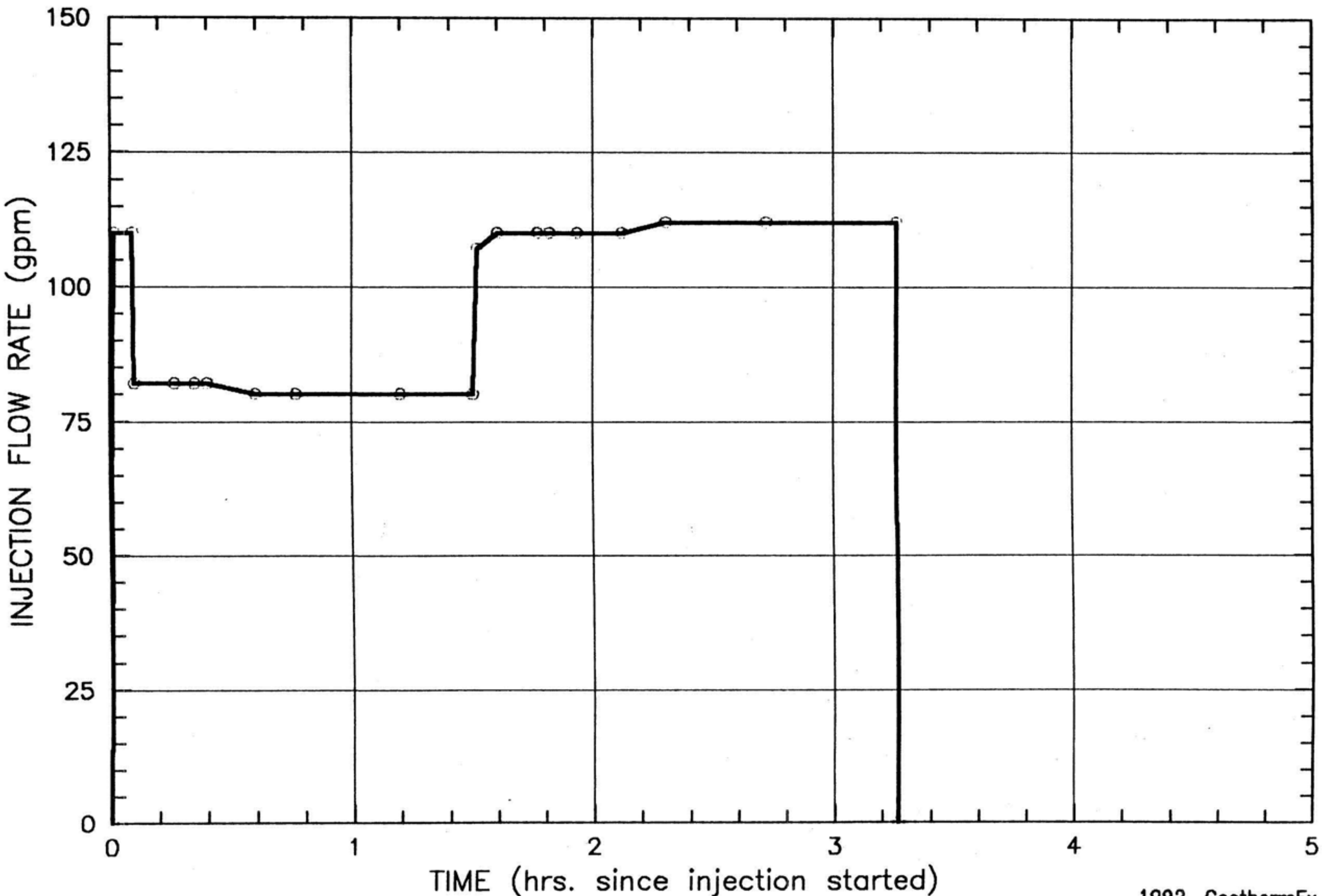


Figure 6.10: PRESSURE BUILDUP ANALYSIS, WELL KS–3 (Horner Plot)



1992, GeothermEx, Inc.

Figure 6.11: INJECTION FLOW RATE vs TIME, WELL SOH-1



1992, GeothermEx, Inc.

Figure 6.12: PRESSURE FALLOFF ANALYSIS, WELL SOH-1 (Horner Plot)

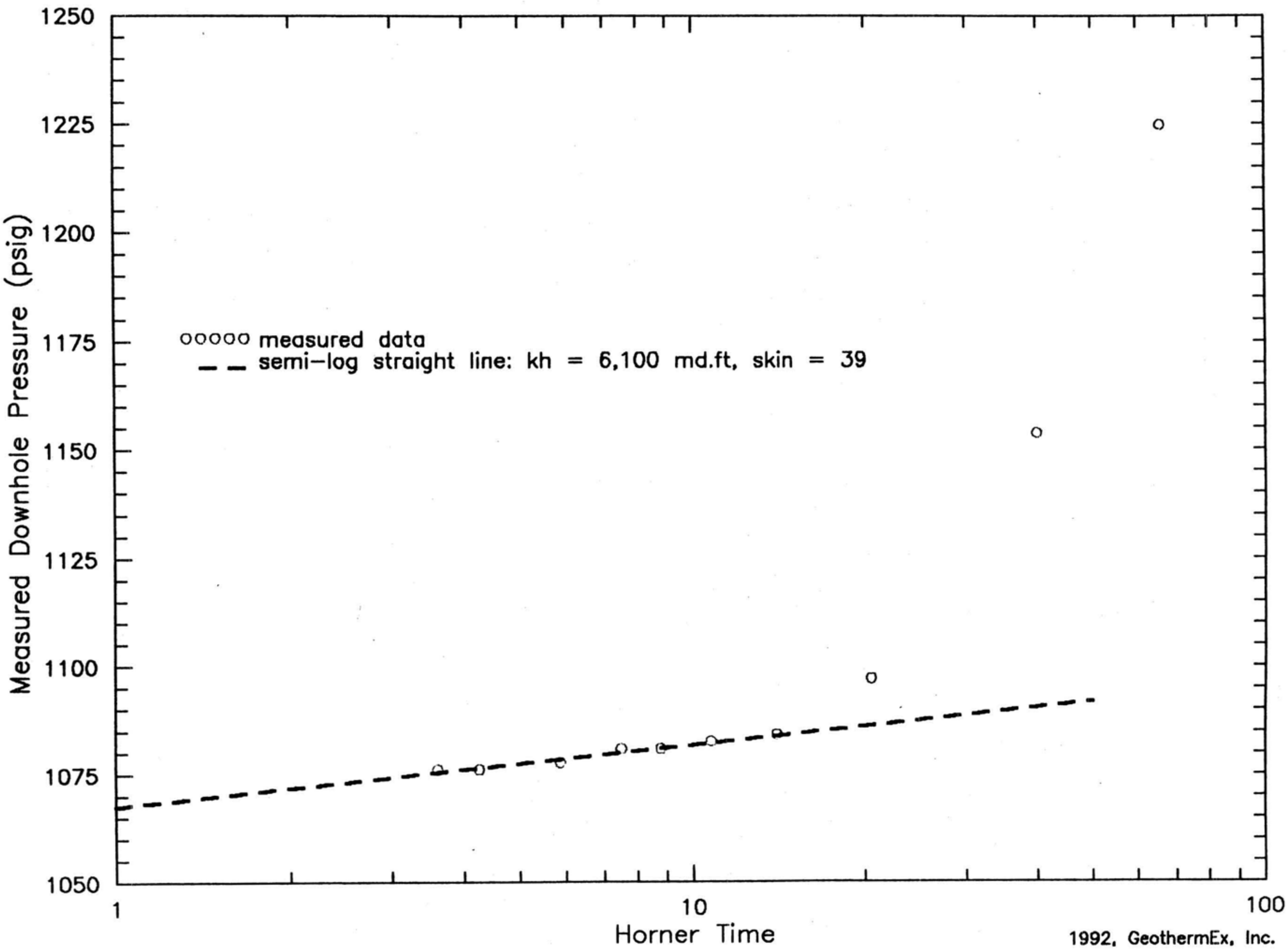


Figure 6.13: MEASURED AND CALCULATED PRESSURE RESPONSES, WELL SOH-1

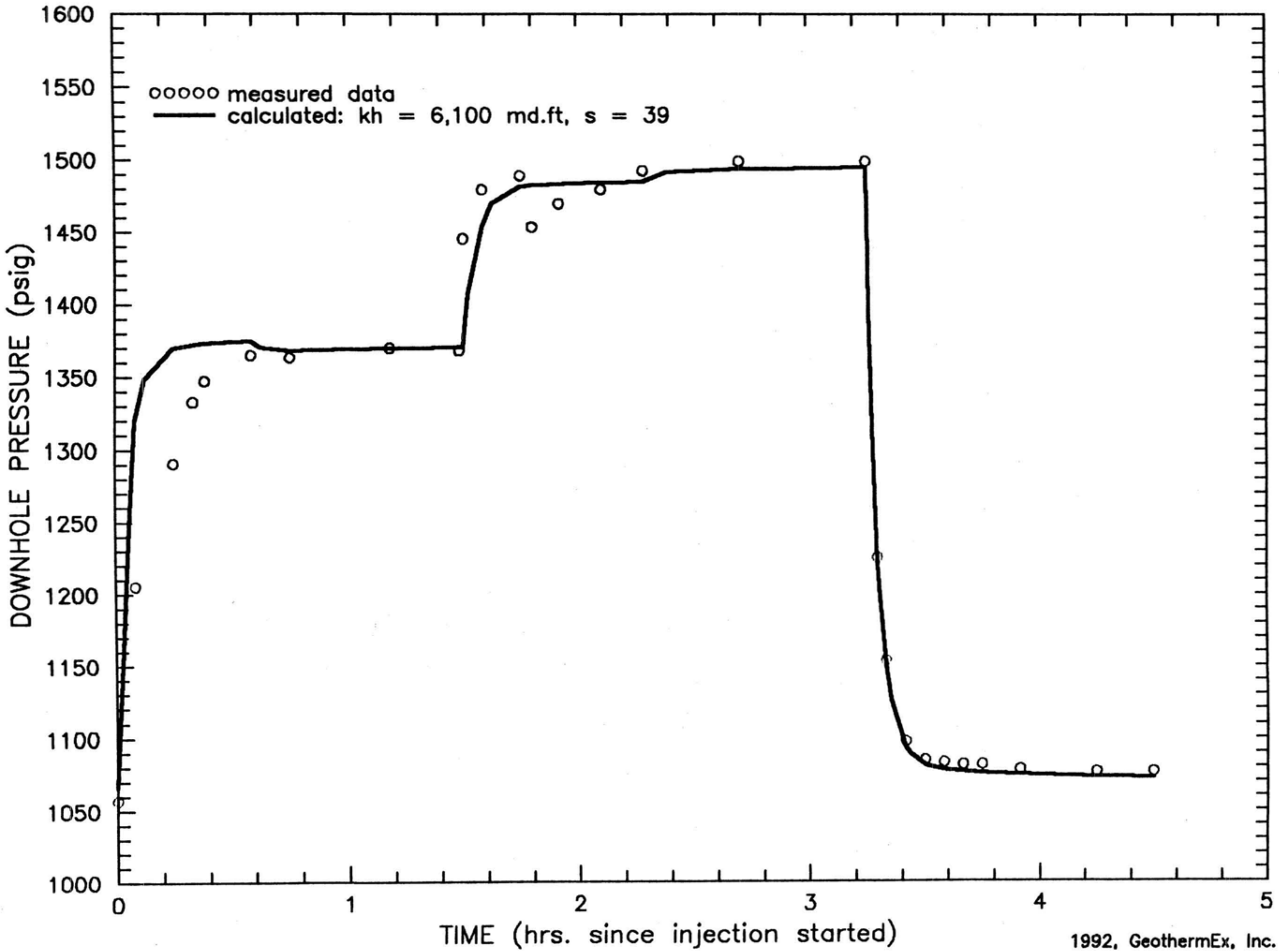


Figure 6.14: INJECTION FLOW RATE vs TIME, WELL SOH-2

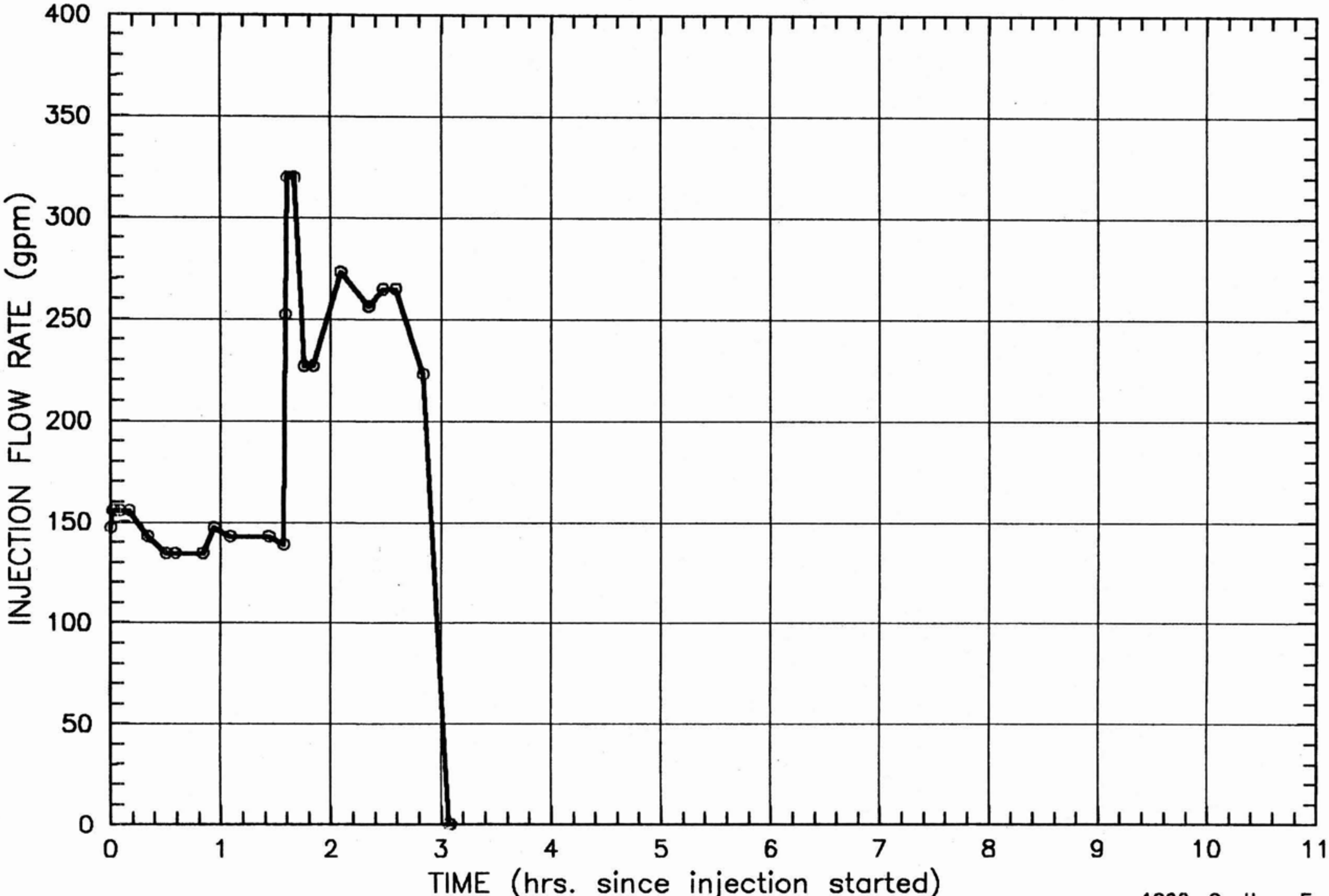


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Figure 6.15: PRESSURE FALLOFF ANALYSIS, WELL SOH-2 (Horner Plot)

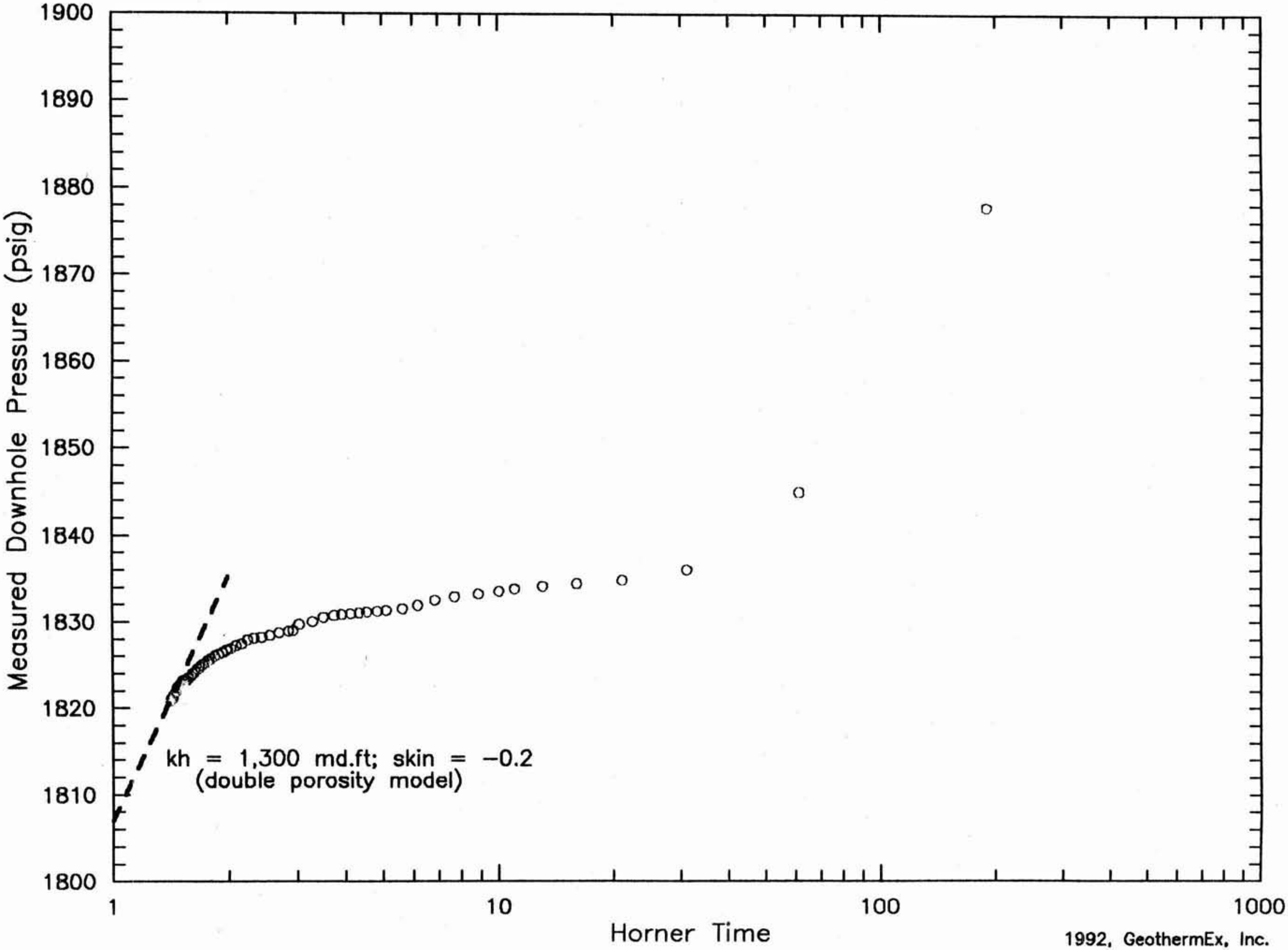


Figure 6.16: MEASURED AND CALCULATED PRESSURE RESPONSES, WELL SOH-2

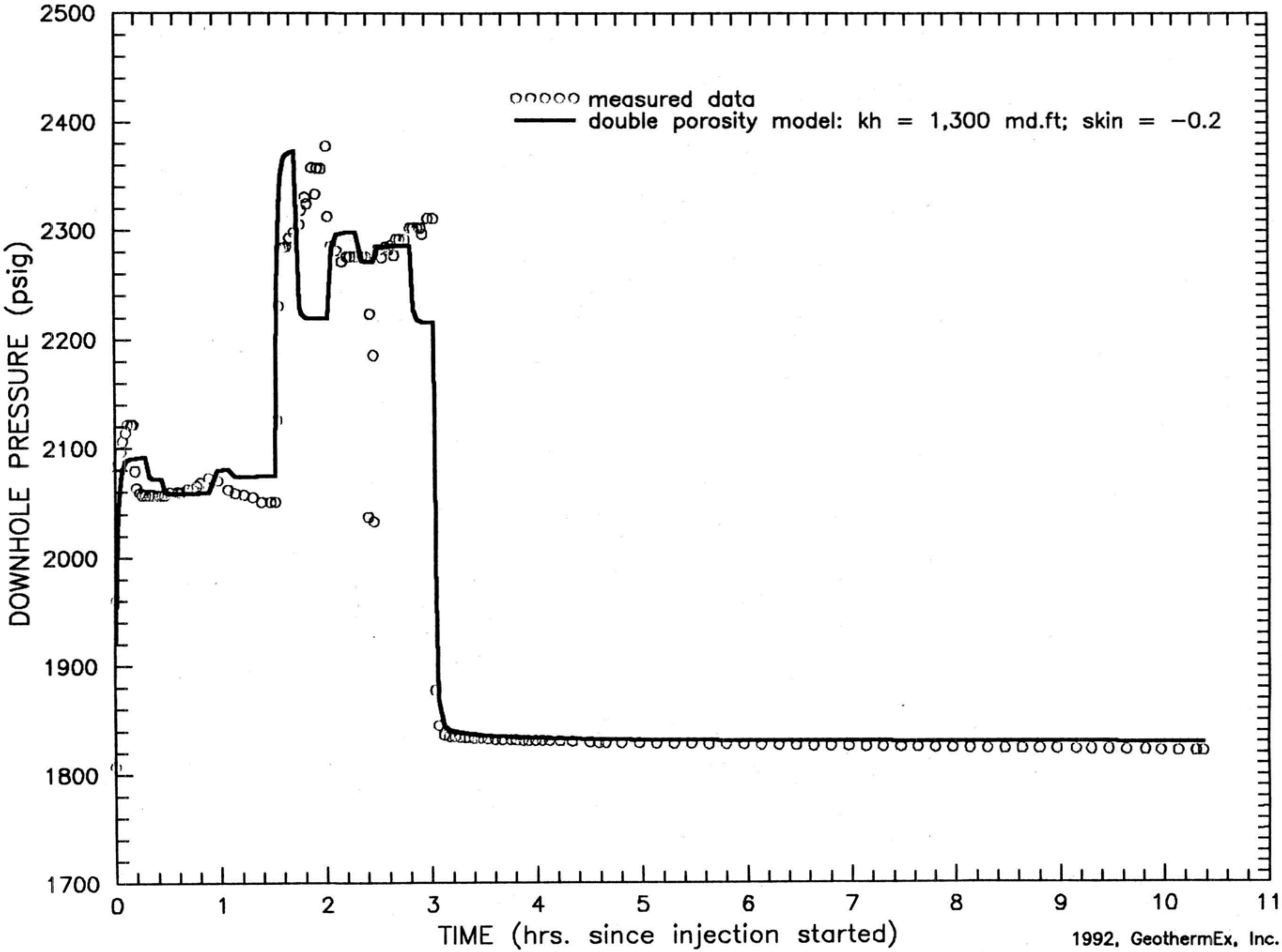
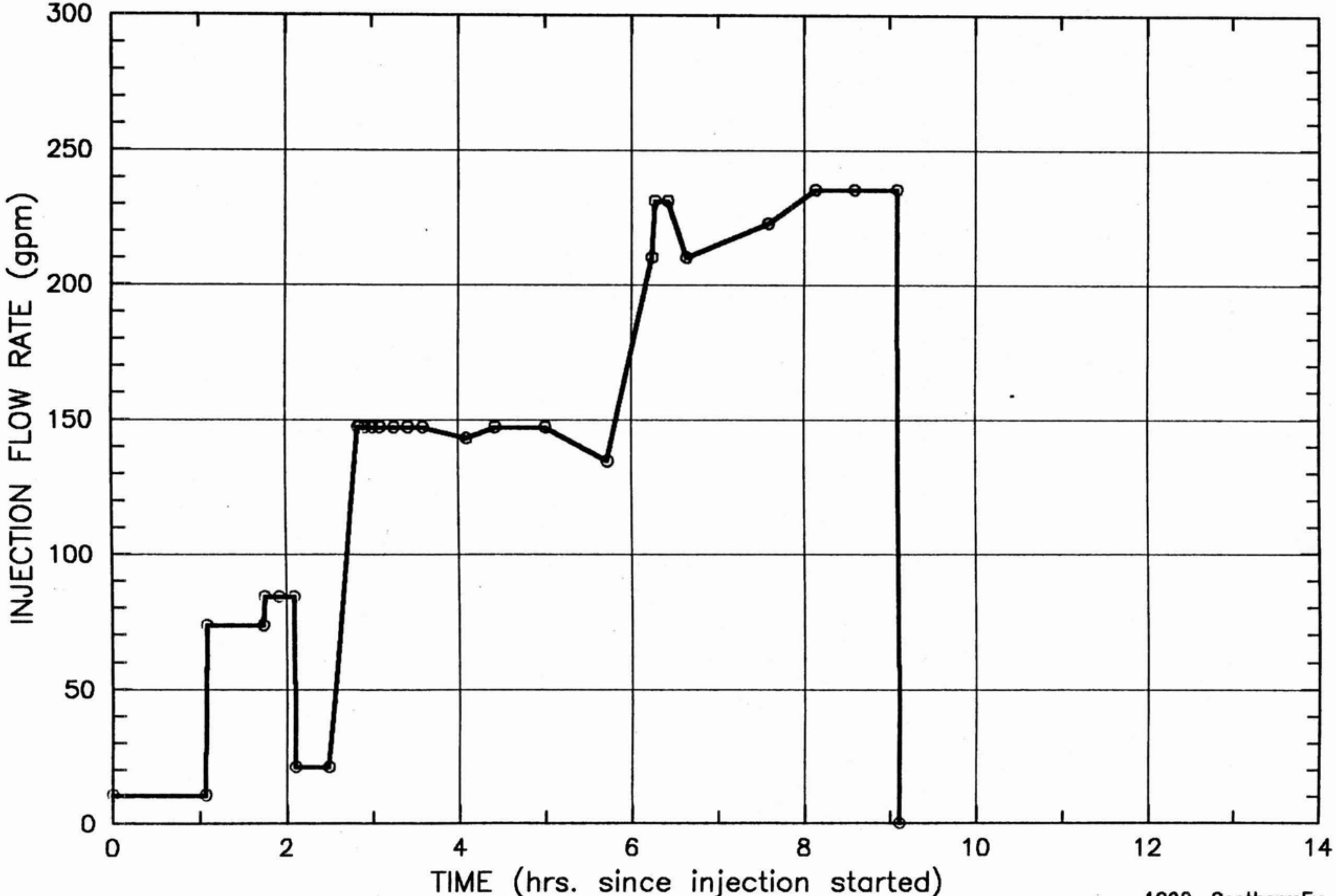


Figure 6.17: INJECTION FLOW RATE vs TIME, WELL SOH-4



1992, GeothermEx, Inc.

Figure 6.18: PRESSURE FALLOFF ANALYSIS, WELL SOH-4 (Horner Plot)

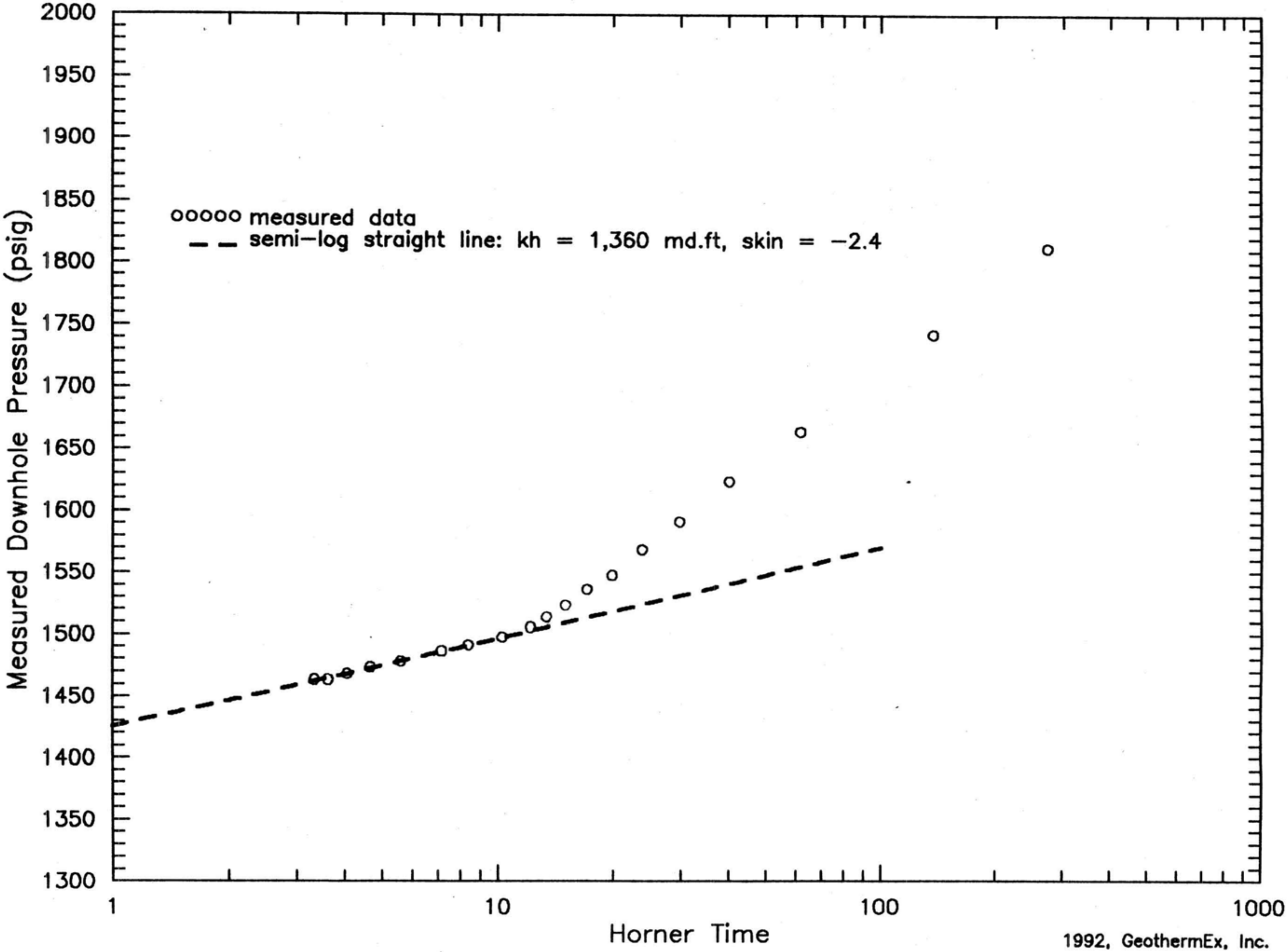
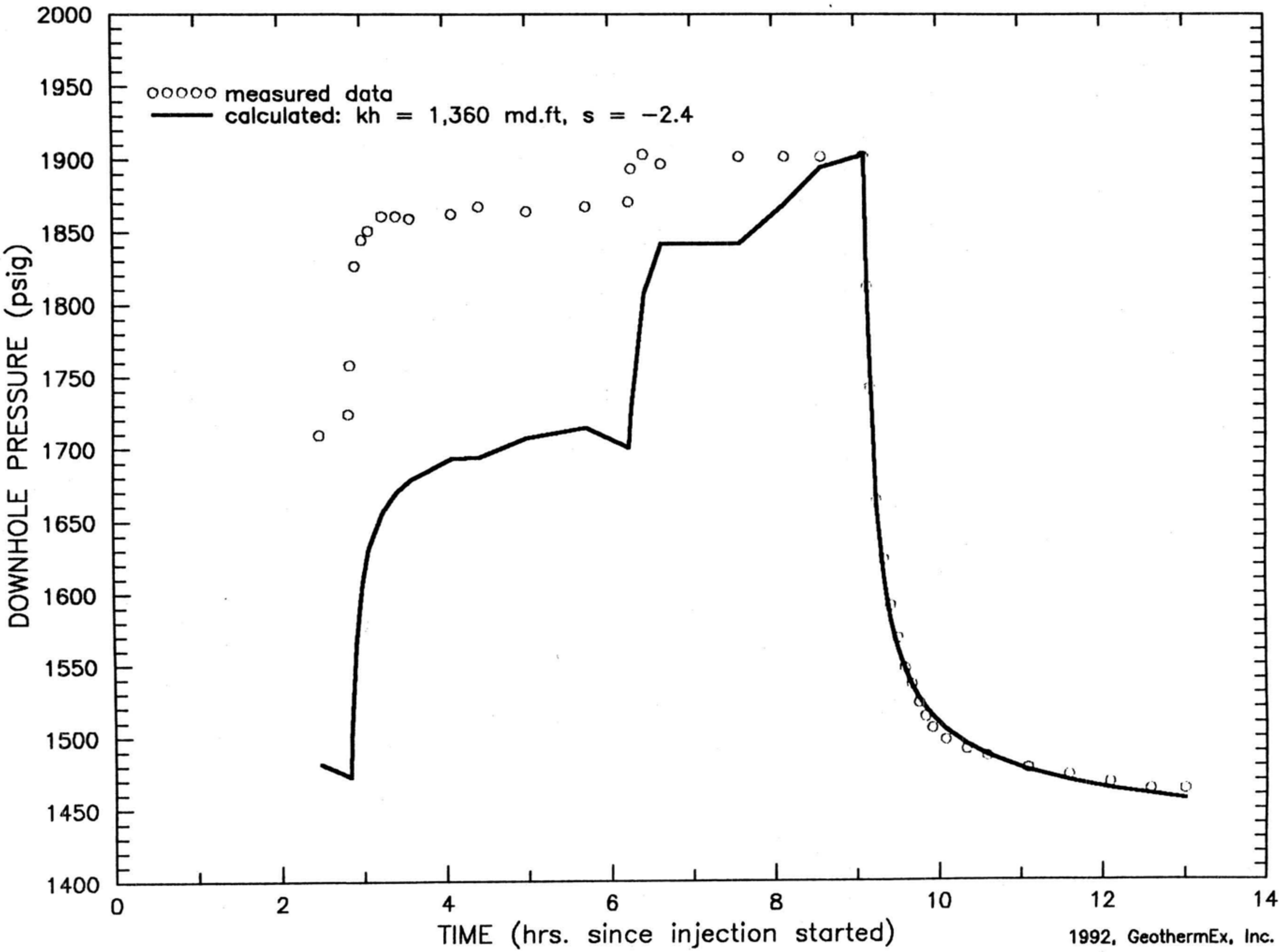


Figure 6.19: MEASURED AND CALCULATED PRESSURE RESPONSES, WELL SOH-4



1992, GeothermEx, Inc.

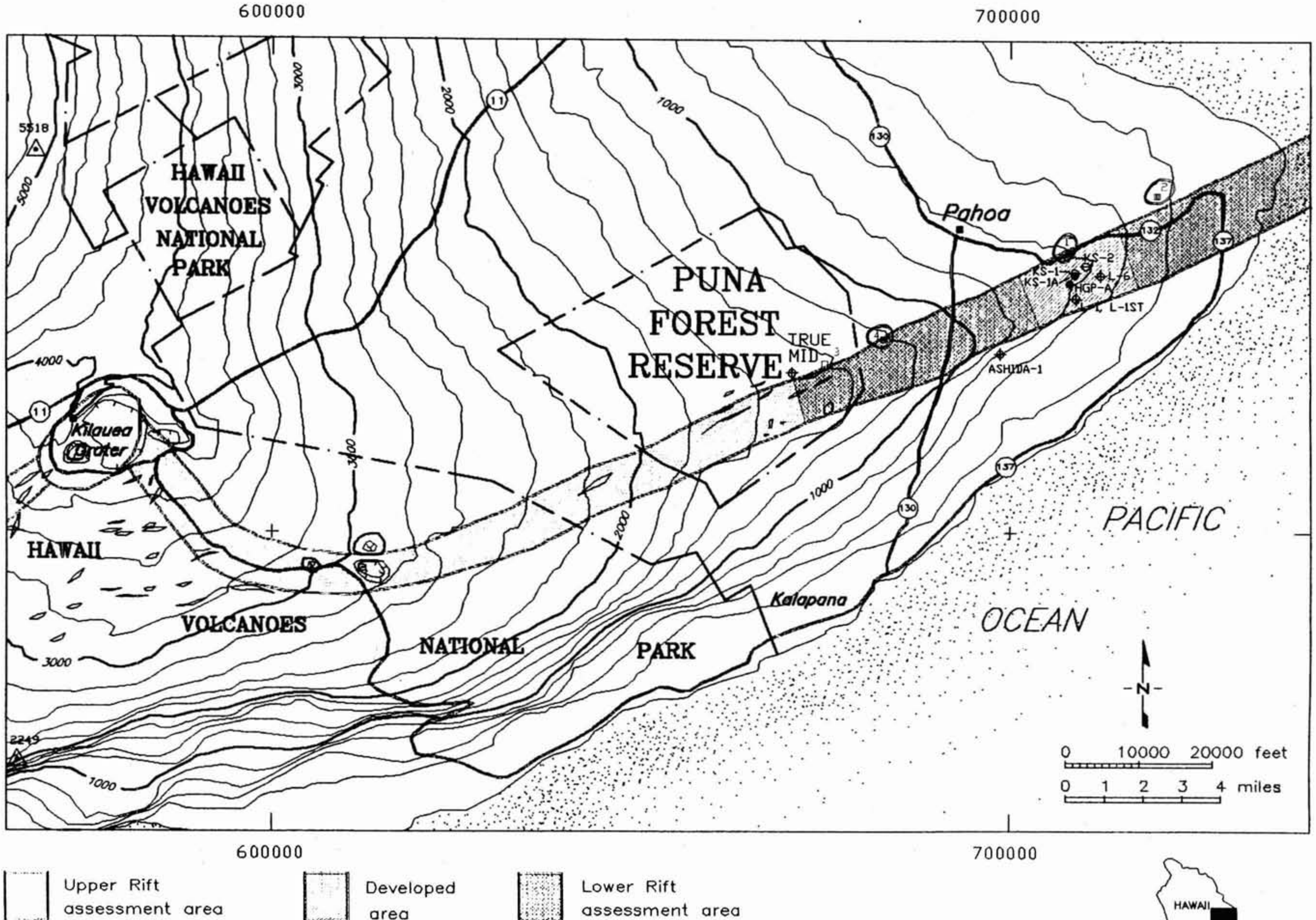


Figure 6.20 : Map of East Rift showing the locations of the Developed Area, the Lower Rift and the Upper Rift assessment areas

1992, GeothermEx, Inc.

PUNARIFT/072392/H4562/EIMN1=20000/PUNA.JP

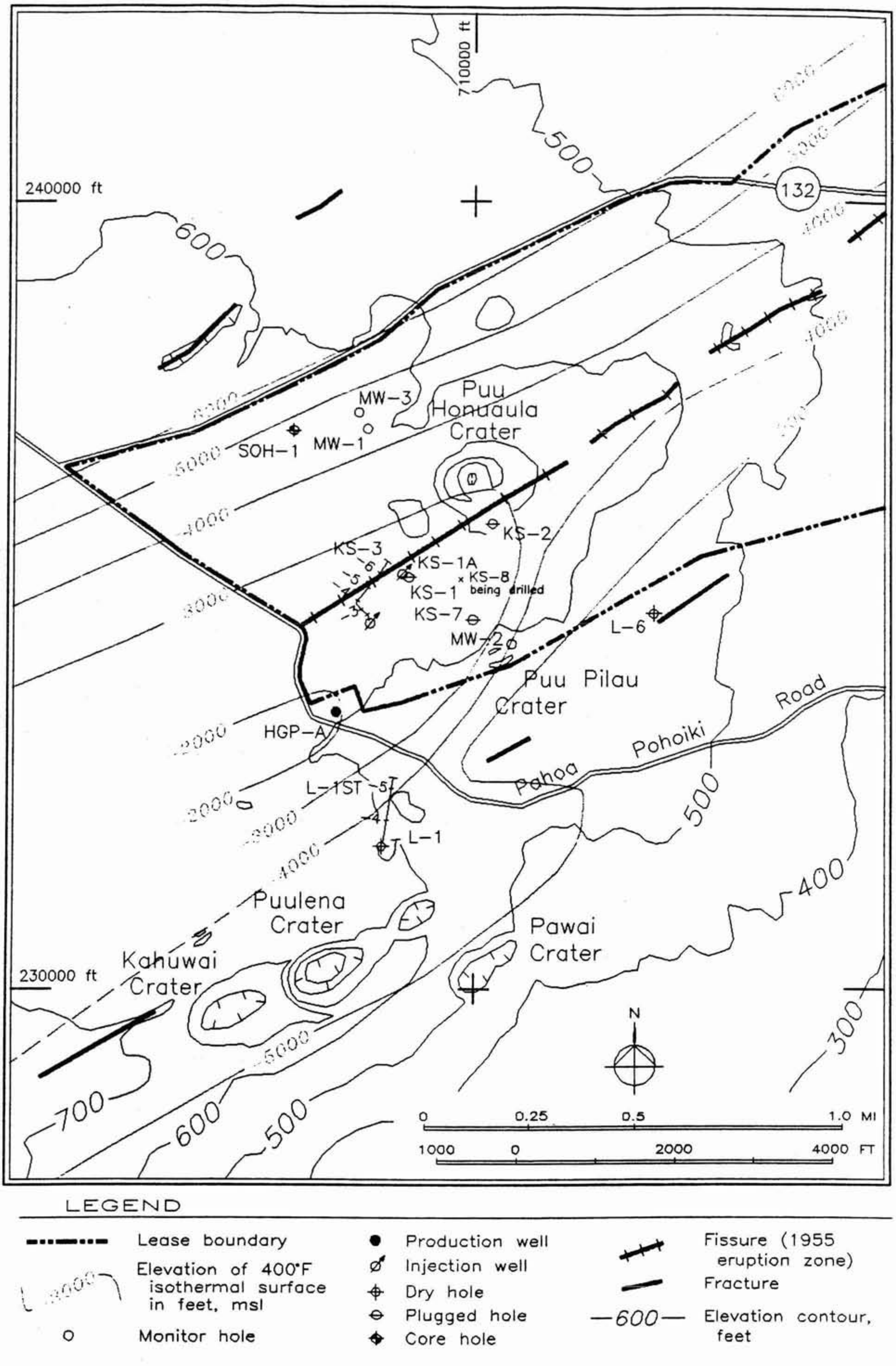


Figure 6.21: Map of the Developed Area showing well locations and the configuration of the 400°F isothermal surface.

1992, GeothermEx, Inc. DBPUF621/072392/H4619/EIMY1=1800/HAWAII.JP

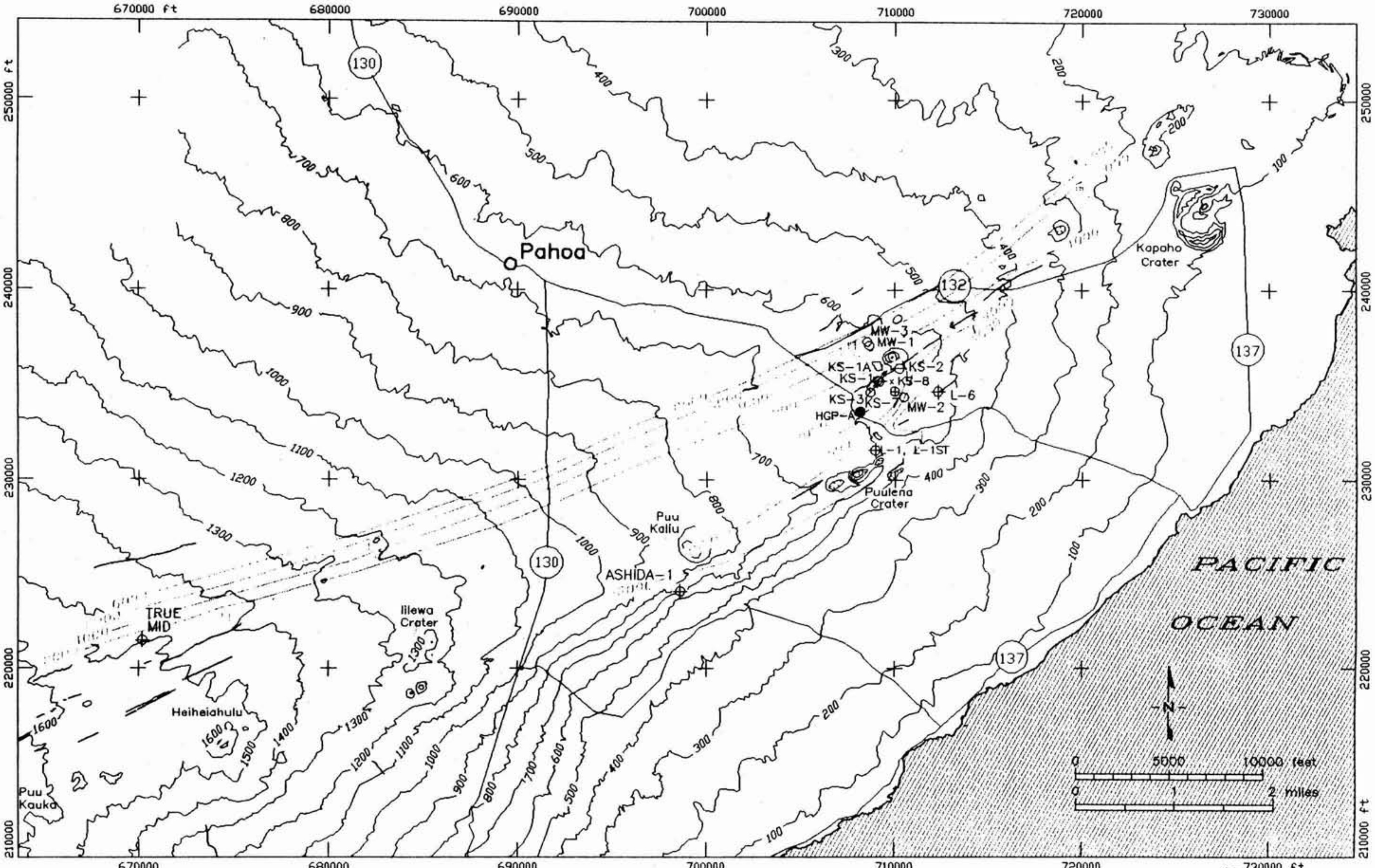
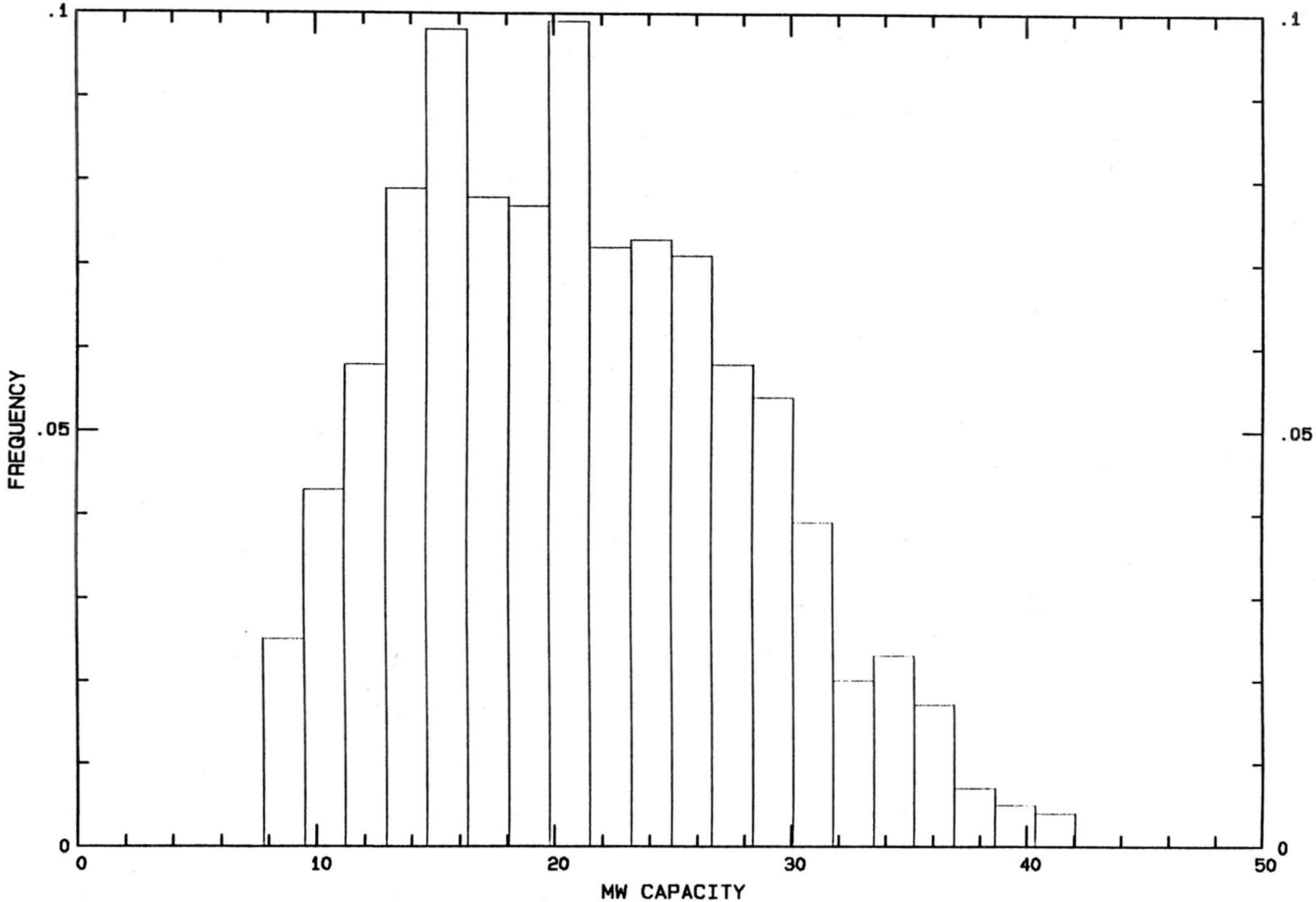


Figure 6.22: Map of the Lower Rift assessment area showing well locations and the configuration of the 400°F isothermal surface

FIGURE 6.23: HISTOGRAM OF MW CAPACITY, KERZ, DEVELOPED AREA



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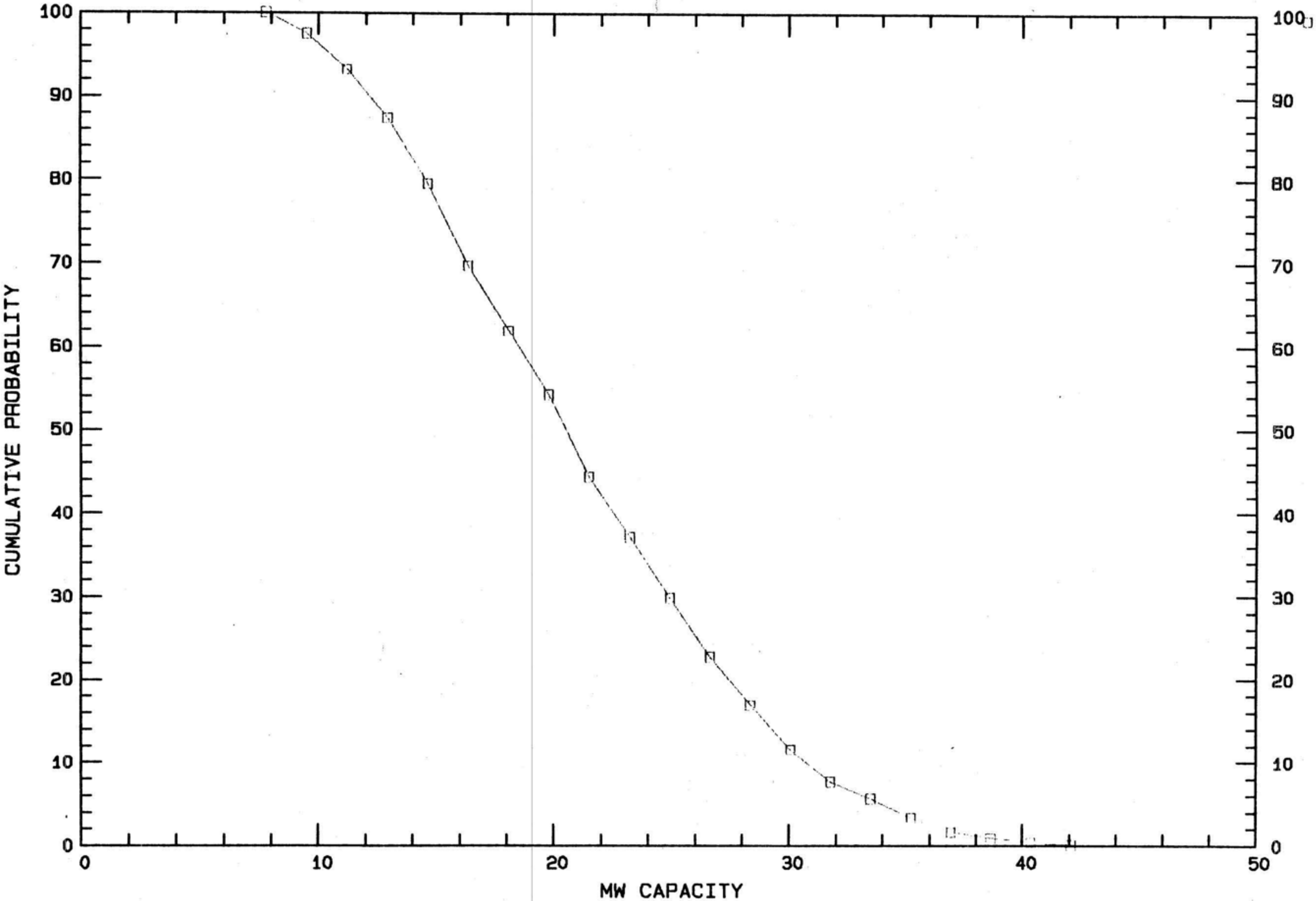
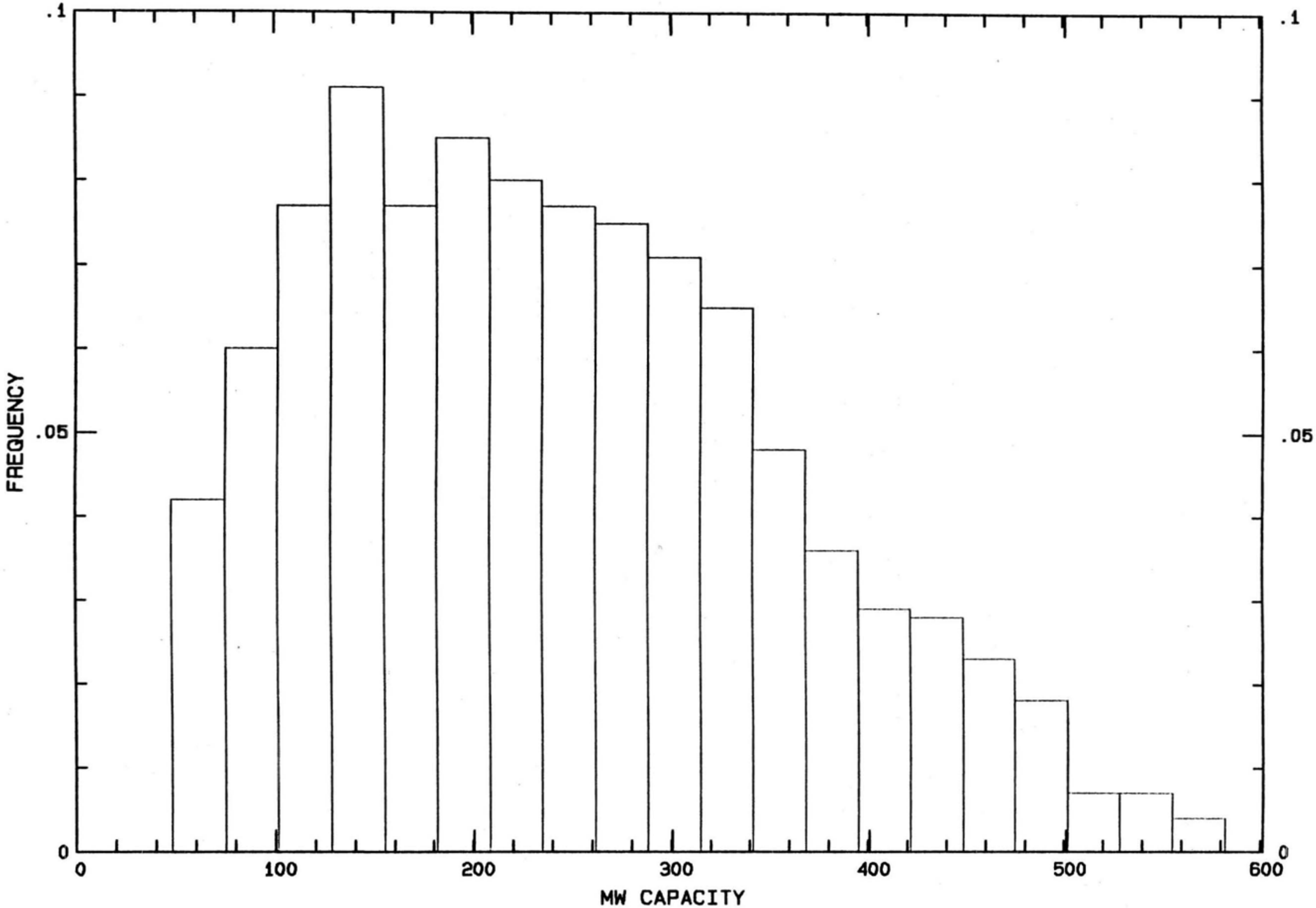
07-08-1992 KERZ1HIS.PLT

FIGURE 6.24: CUMULATIVE PROBABILITY OF MW CAPACITY, KERZ, DEVELOPED AREA



GeothermEx, Inc.
07-08-1992 KERZ1CMP.PLT

FIGURE 6.25: HISTOGRAM OF MW CAPACITY, KERZ, UNDEVELOPED LOWER RIFT AREA



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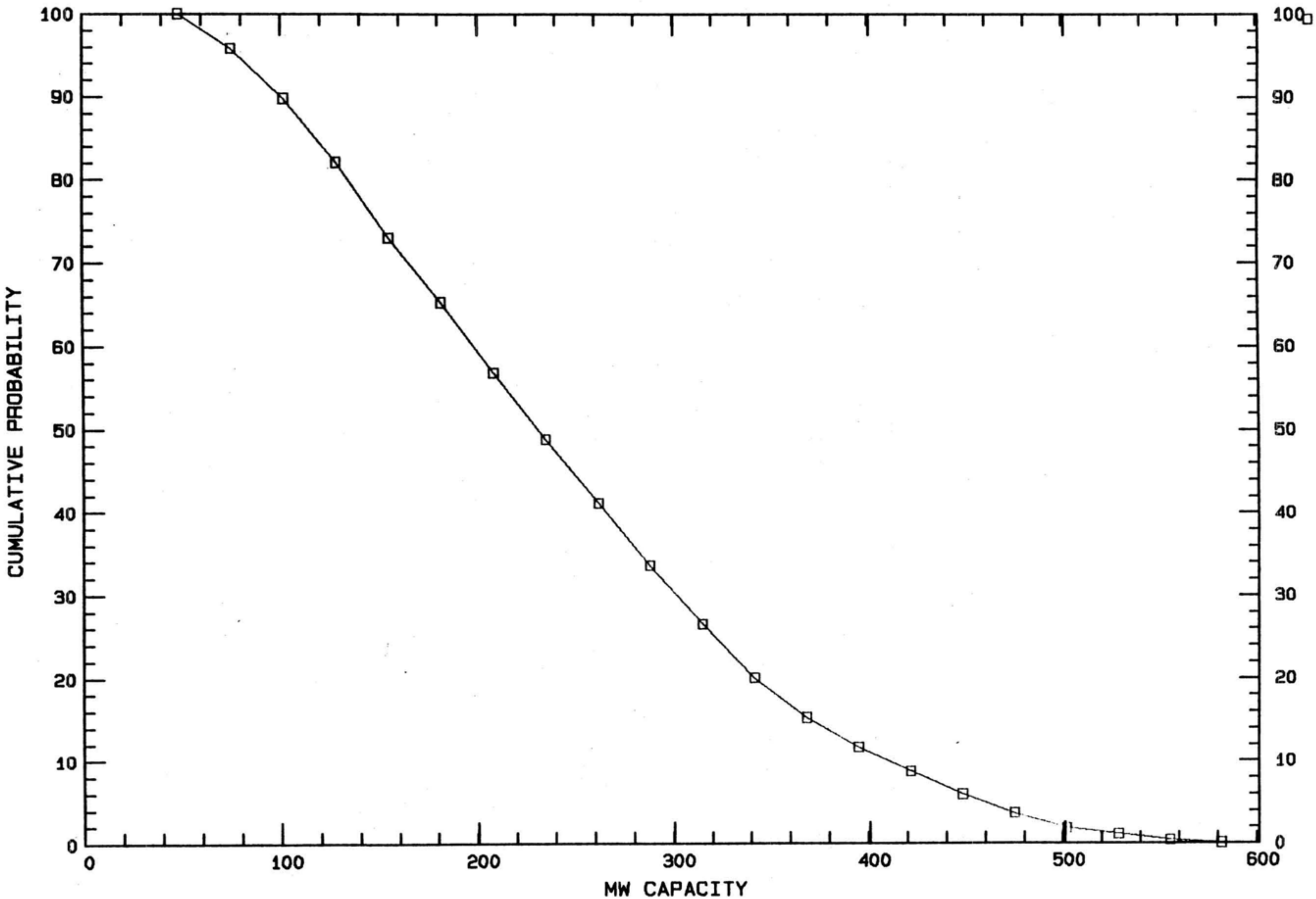
07-08-1992 KERZ2HIS.PLT

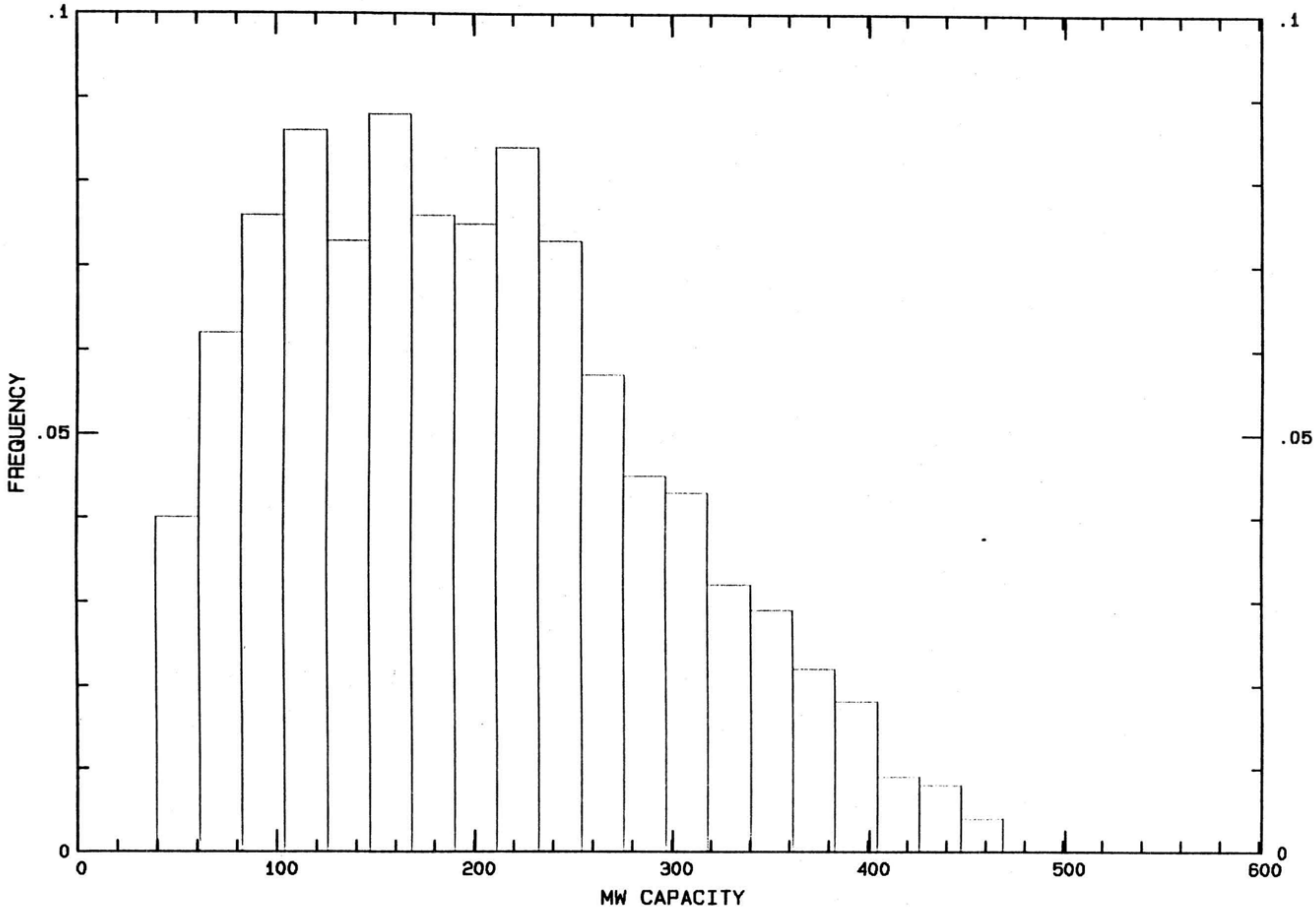
FIGURE 6.26: CUMULATIVE PROBABILITY OF MW CAPACITY, KERZ, UNDEVELOPED LOWER RIFT AREA



GeothermEx, Inc.

07-08-1992 KERZ2CMP.PLT

FIGURE 6.27: HISTOGRAM OF MW CAPACITY, KERZ, UPPER RIFT AREA



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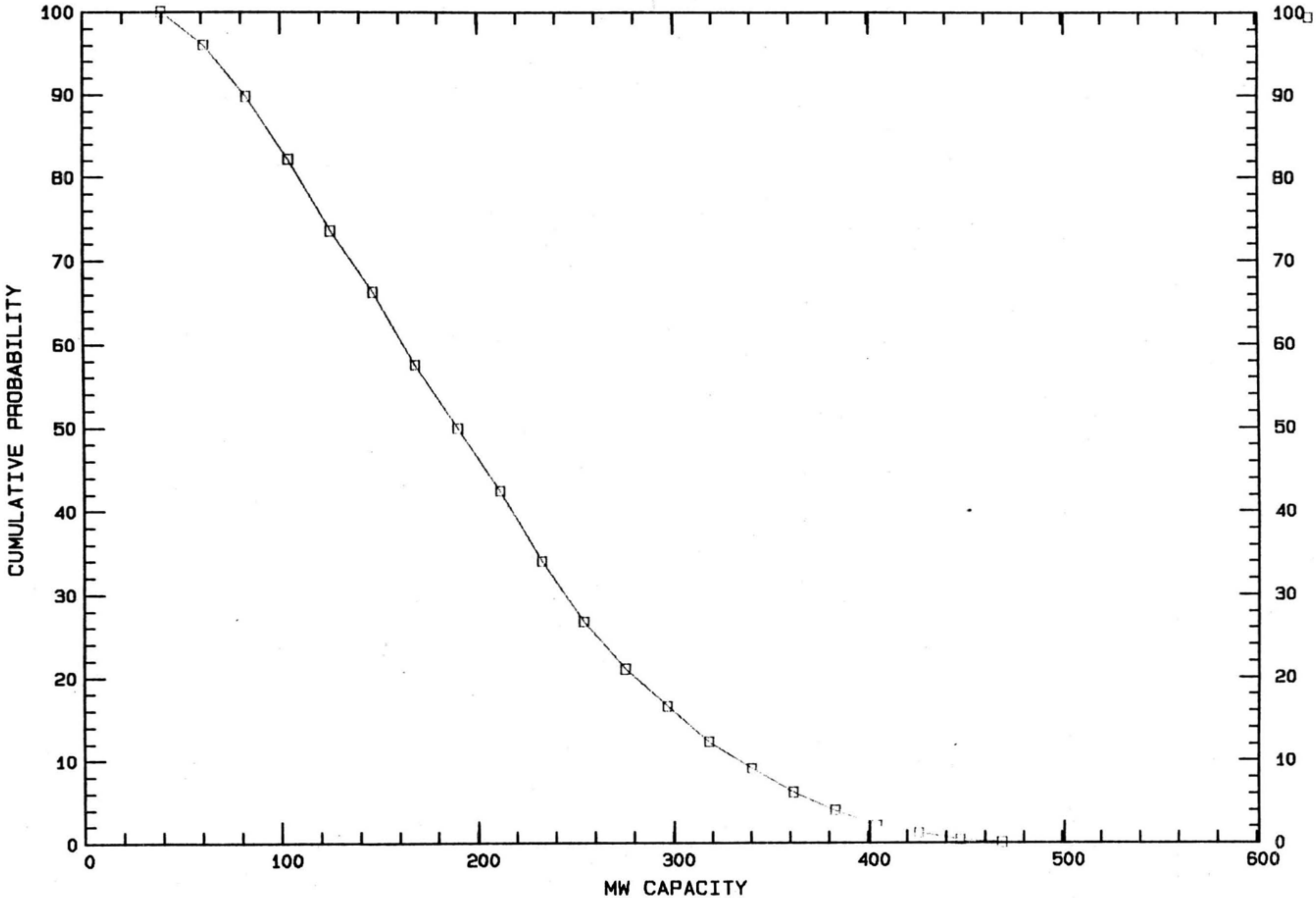
07-08-1992 KERZ3HIS.PLT

FIGURE 6.28: CUMULATIVE PROBABILITY OF MW CAPACITY, KERZ, UPPER RIFT AREA



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07-08-1992 KERZ3CMP.PLT

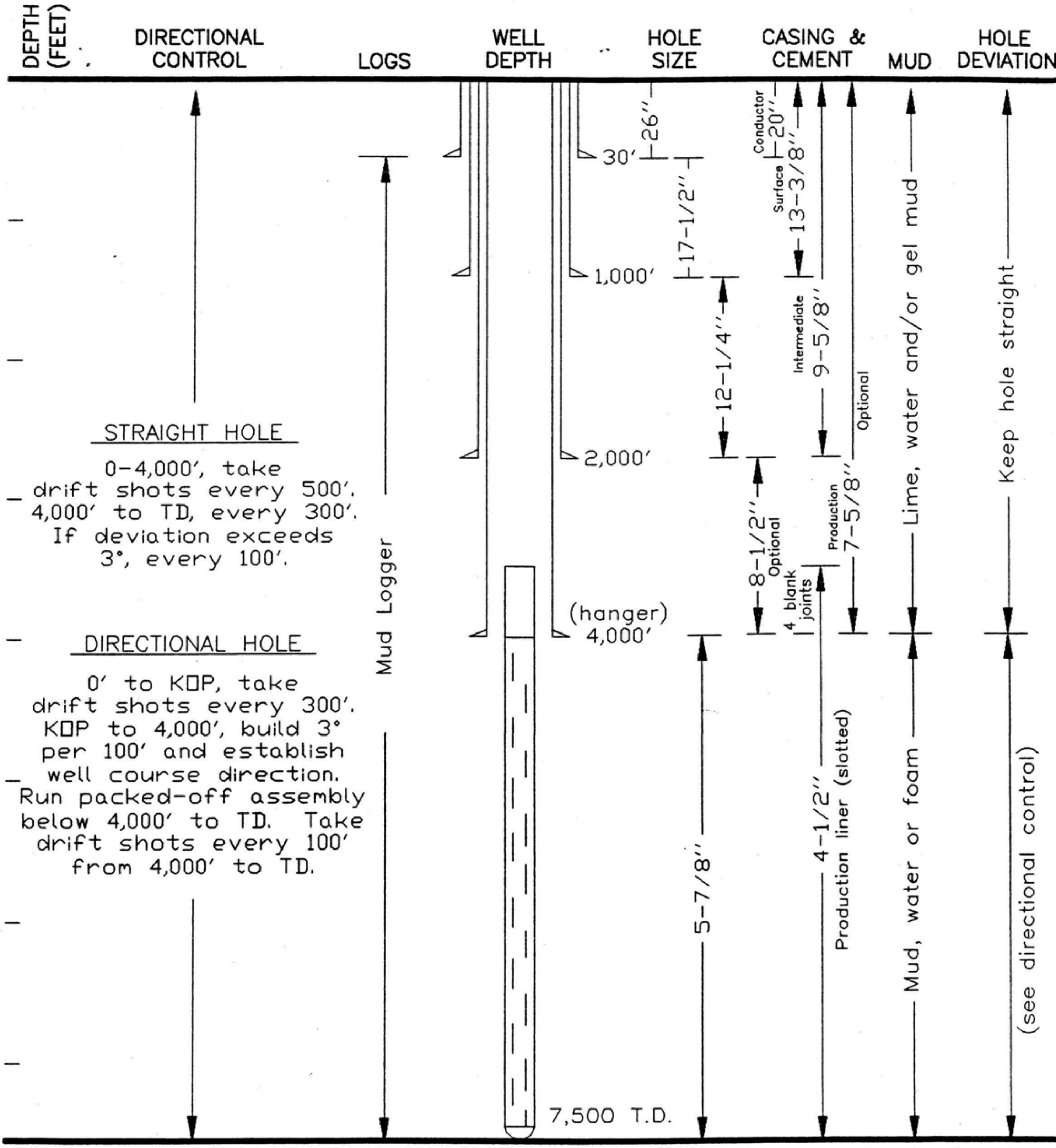
Figure 7.1: **DRILLING WORKSHEET**

TITLE: PUNA K.G.R.A.

WELLS: EXPLORATION – SOH

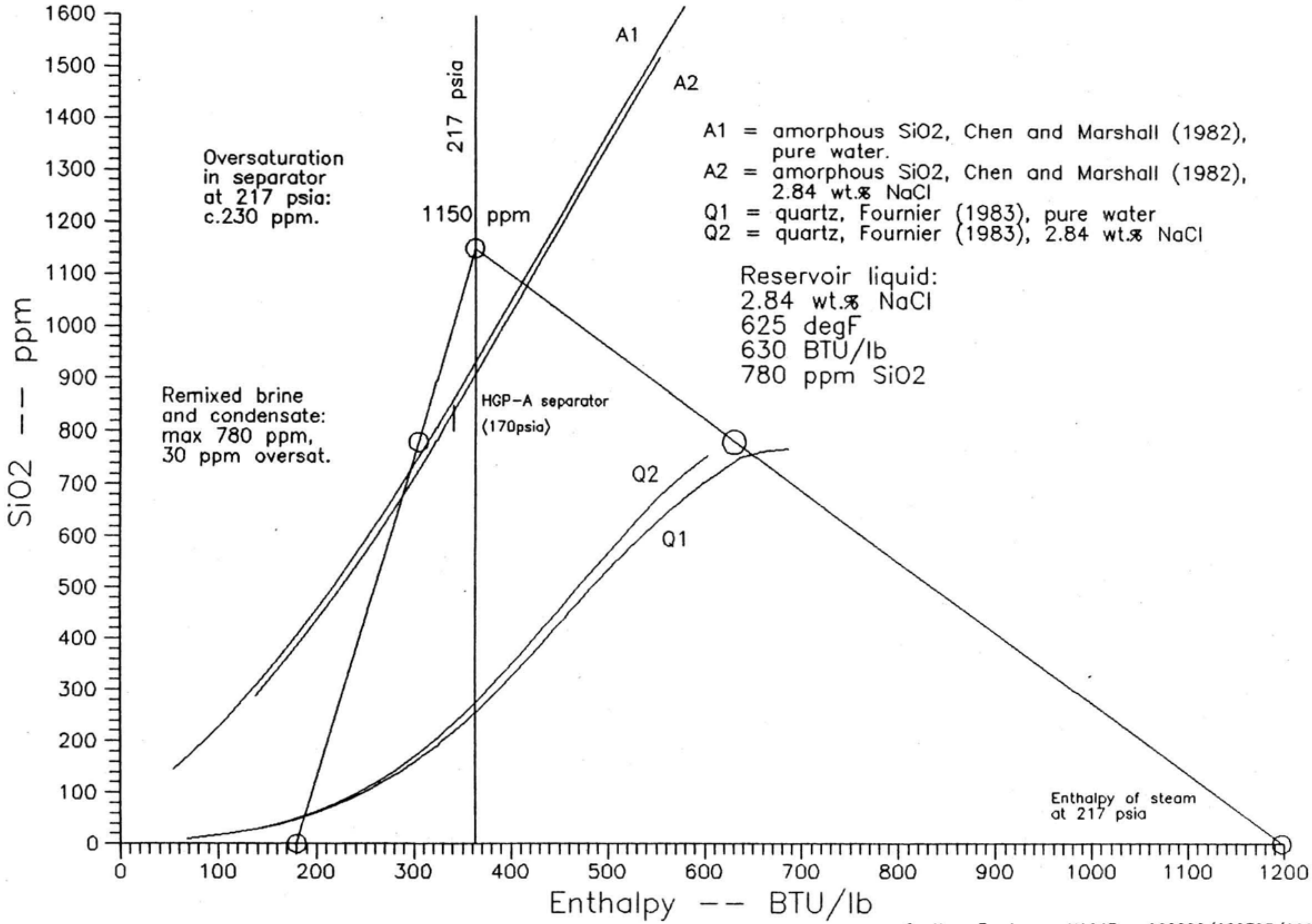
LOCATION:

OBJECTIVE: Drill a water–steam producer to 7,500'



1992, GeothermEx, Inc. DBPUESOH/072392/H4542/EIMY1=1/DBPU.JP

Figure 7.2 : Graph showing process conditions and solubility of silica at saturation enthalpy – PUNA, KERZ



GeothermEx, Inc. K1043 900220/920723/920916

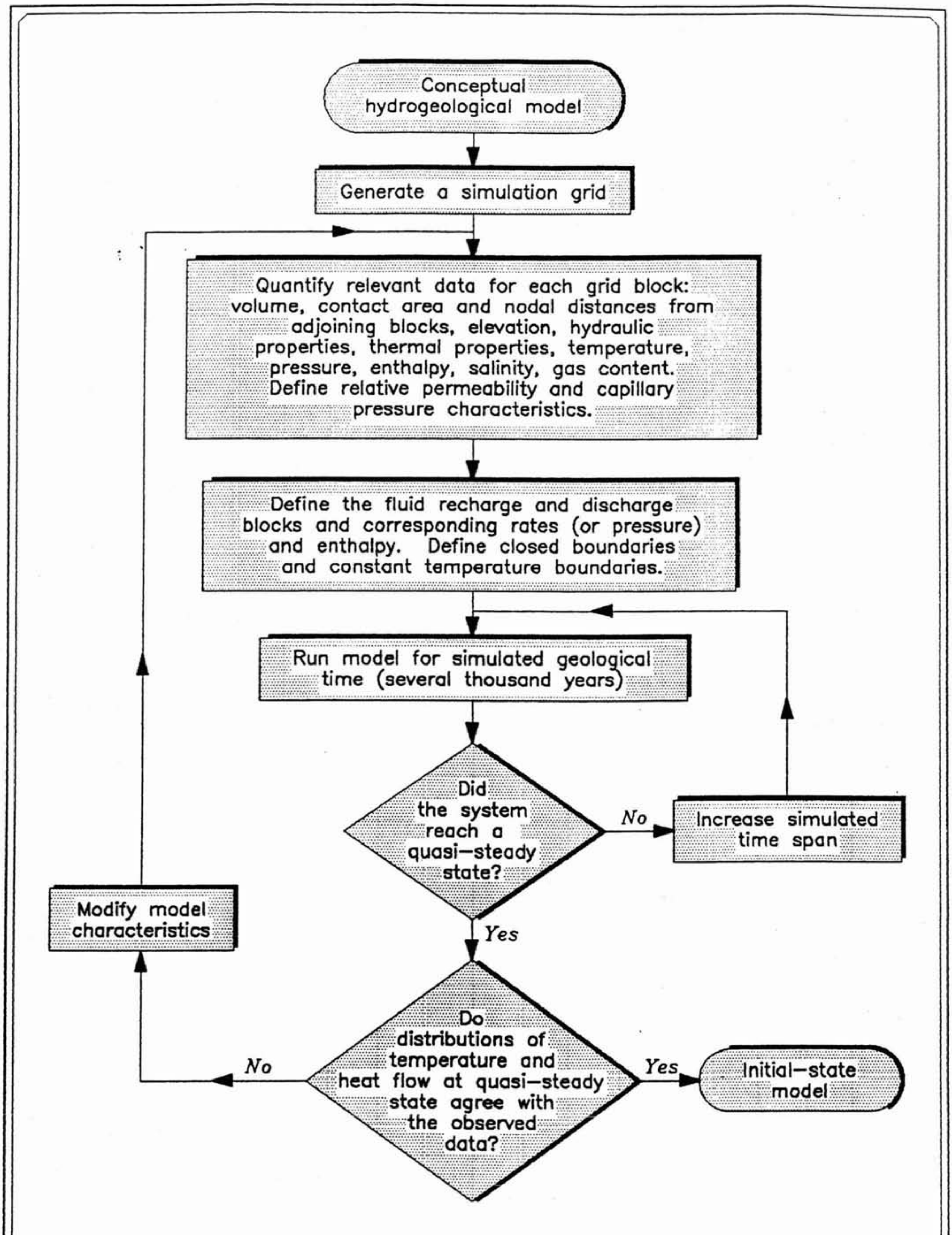


Figure 8.1: Flow chart of numerical simulation of the initial state.

1990. GeothermEx. Inc. HKZUNF28/100490/H2952/EIMY10.5=90/MTCARLO.JP

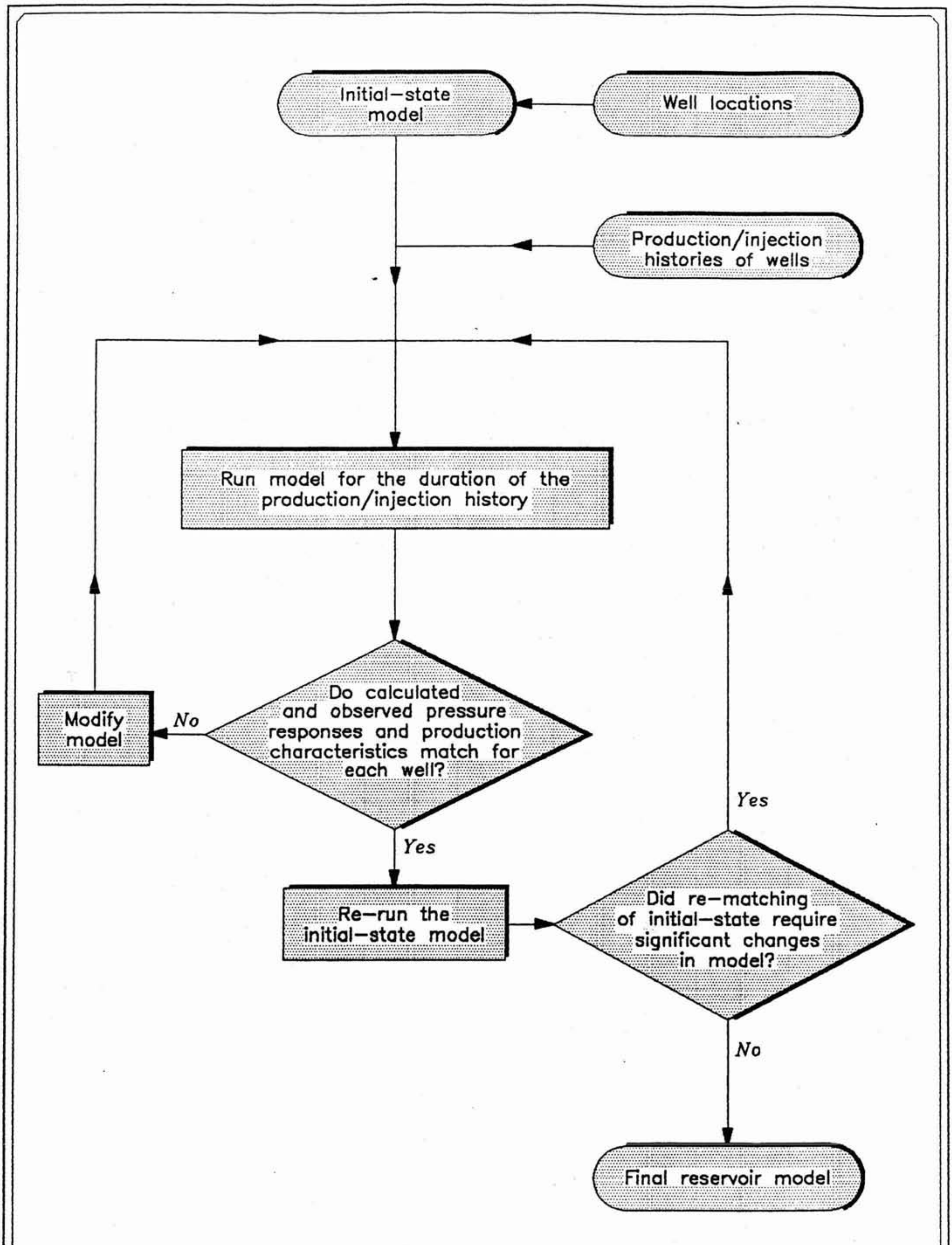


Figure 8.2: Flow chart describing the well test matching procedure.

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:ABLE ADDRESS GEOTHERMEX
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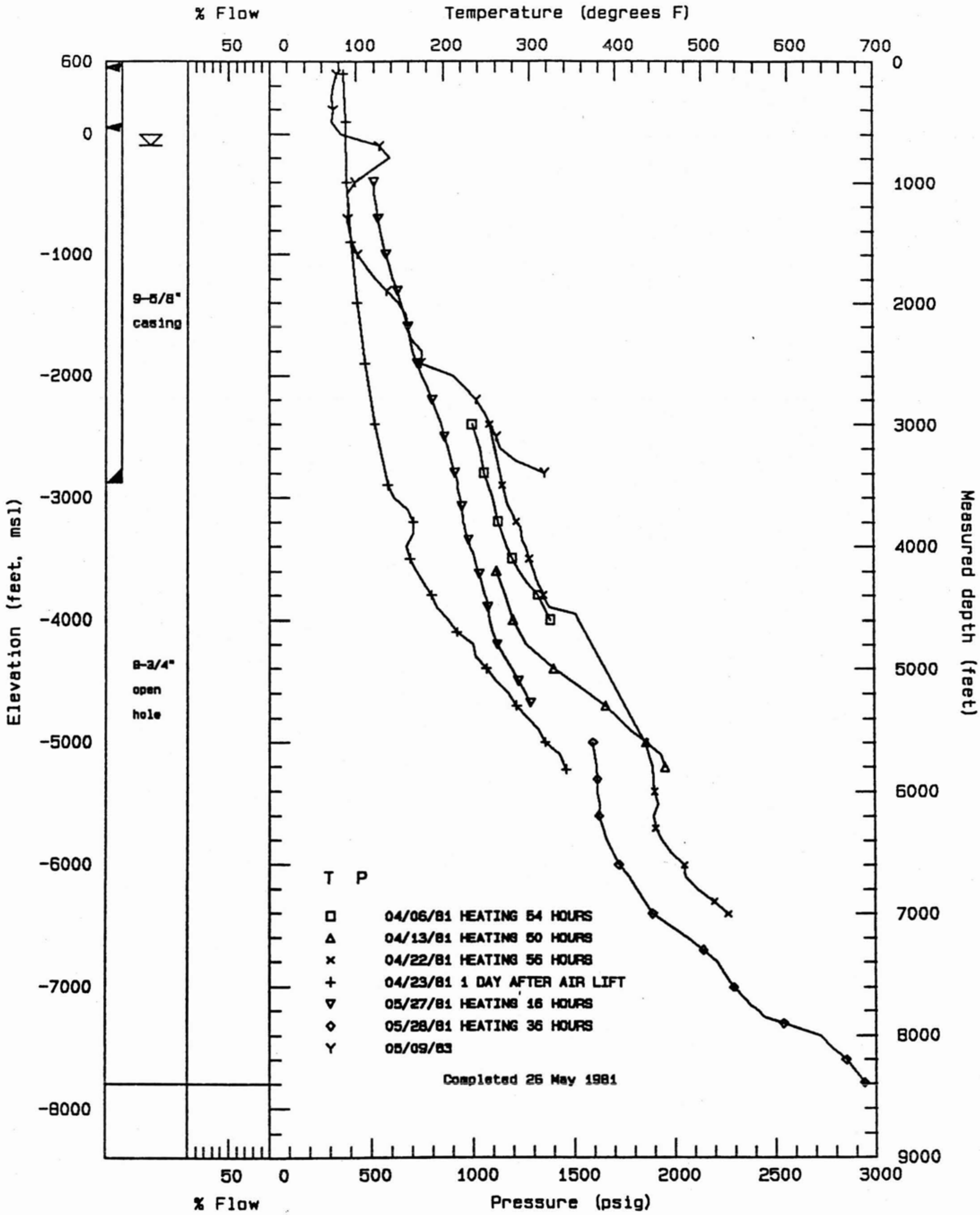
'AX (510) 527-8164

APPENDIX A

Downhole Summary Plots

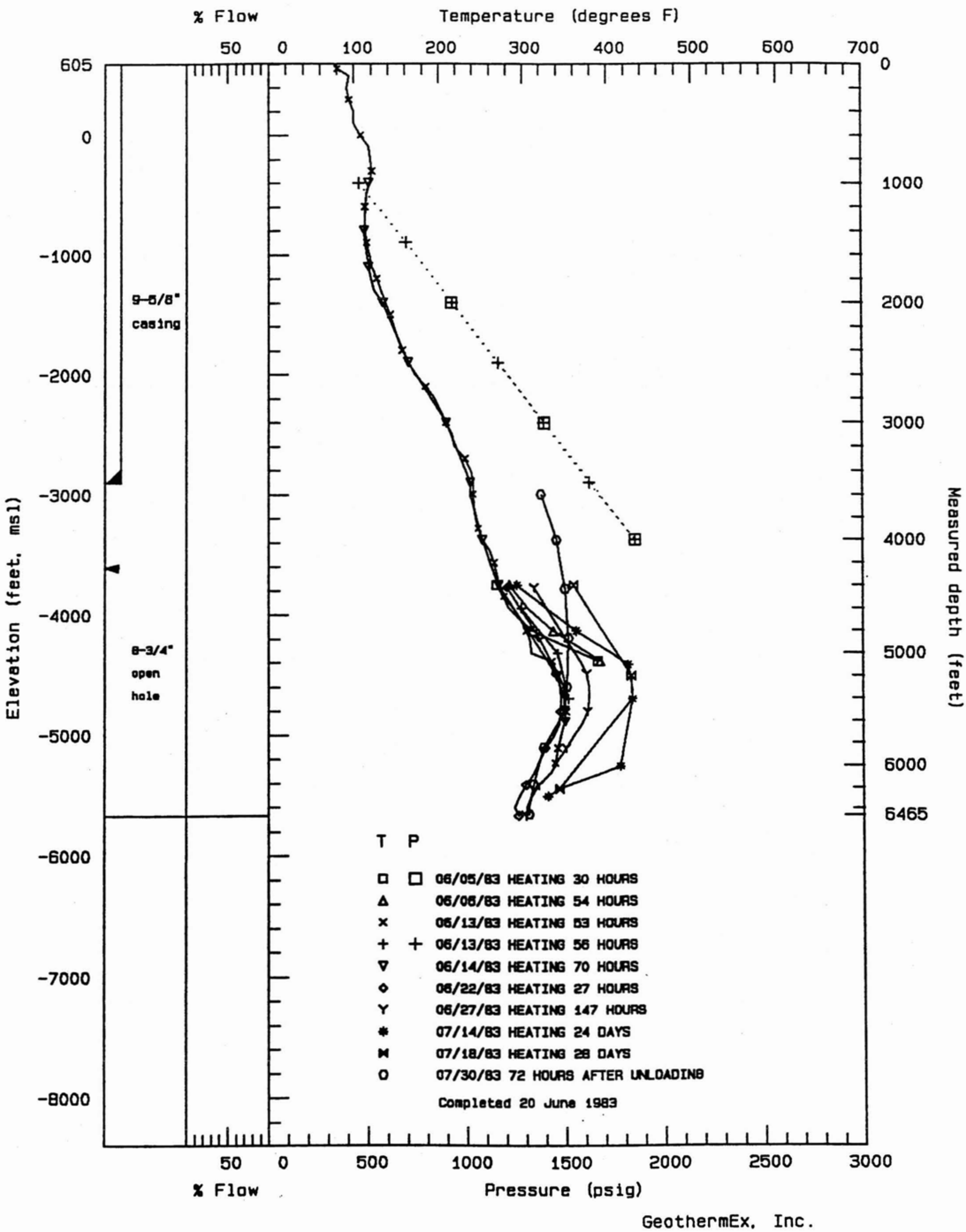
DOWNHOLE SUMMARY PLOT, WELL LANIPUNA 1



GeothermEx, Inc.

1991 T1.PLT

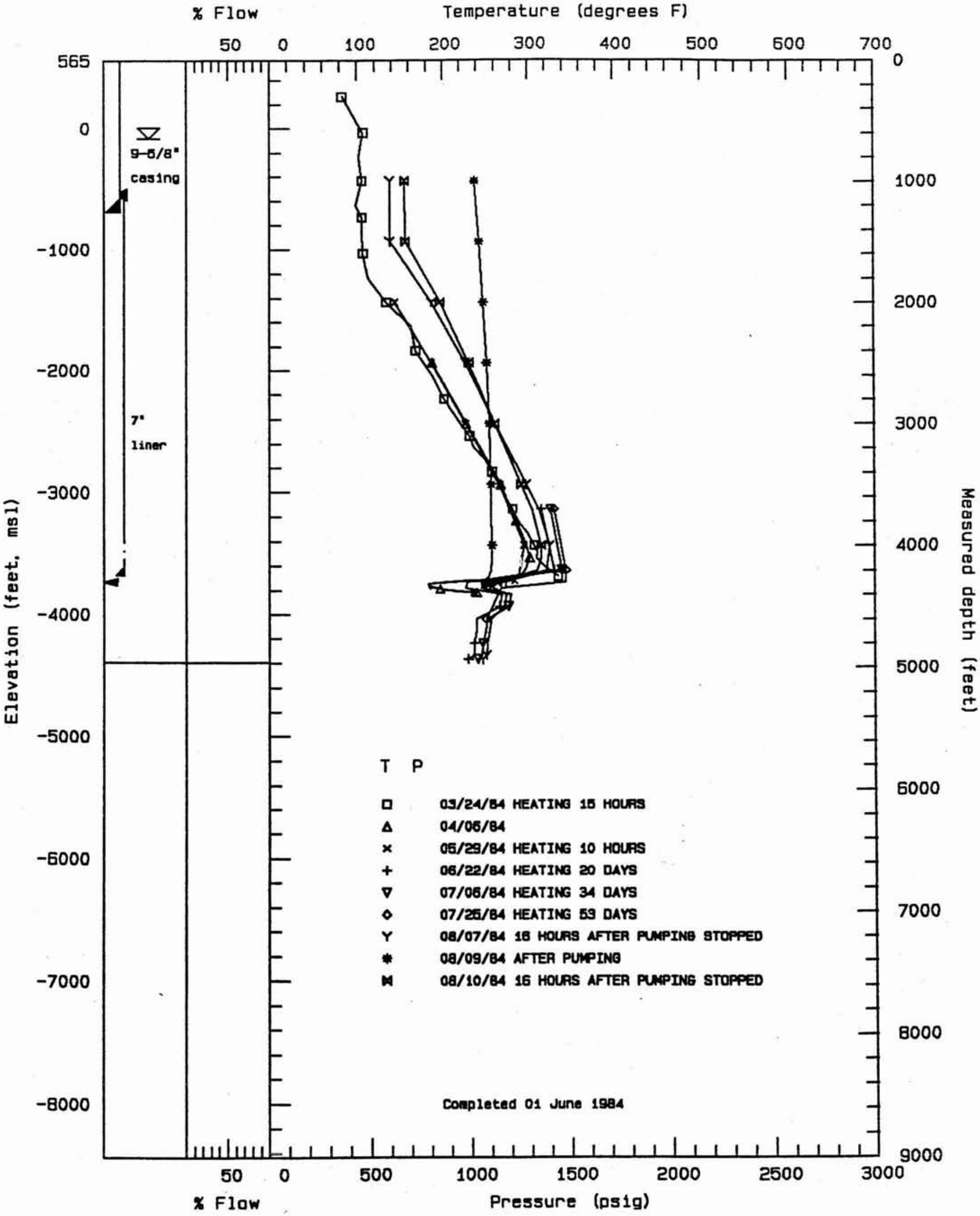
DOWNHOLE SUMMARY PLOT, WELL LANIPUNA 1 ST



GeothermEx, Inc.

1991 TP1.PLT

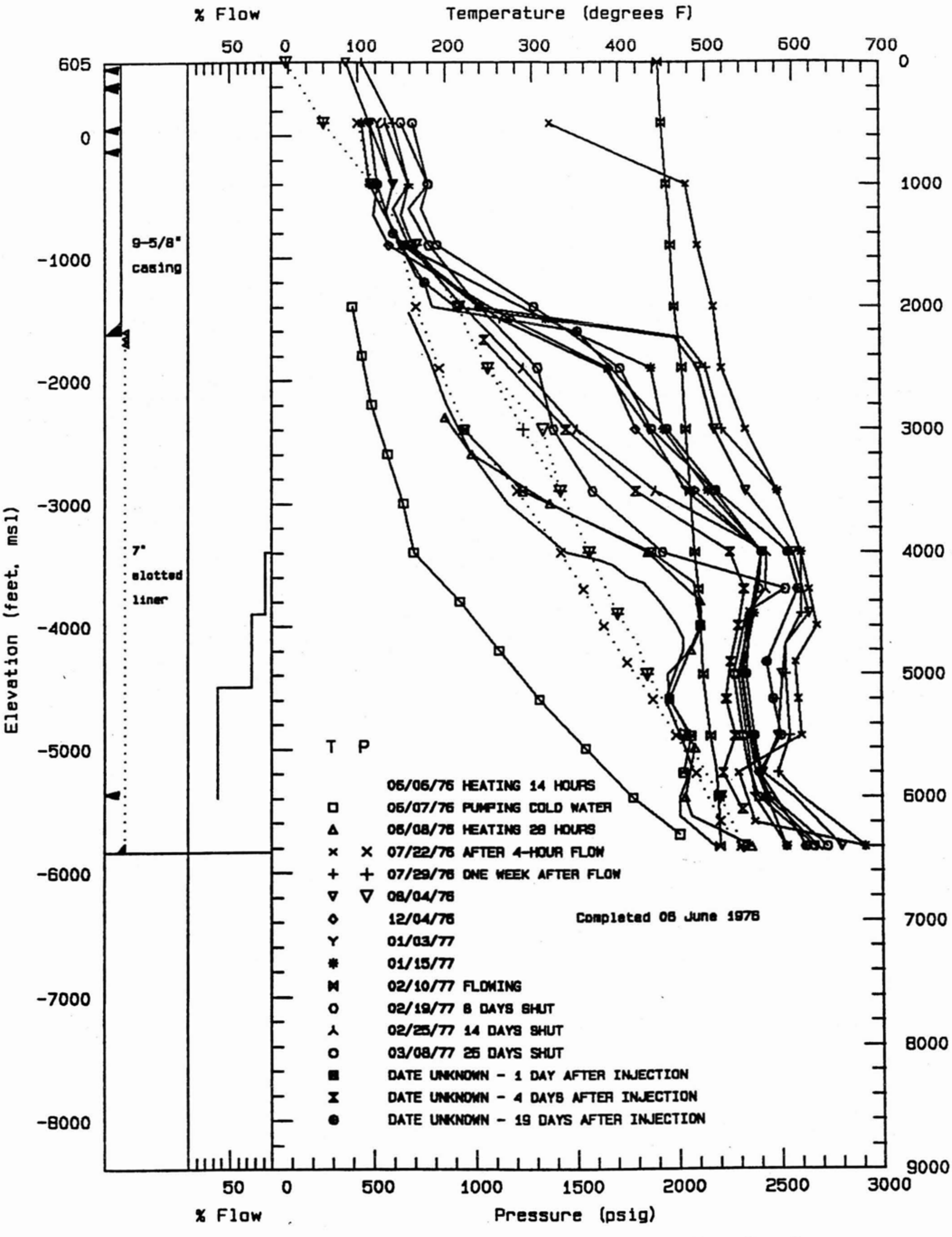
DOWNHOLE SUMMARY PLOT, WELL LANIPUNA 6



GeothermEx, Inc.

1991 T1.PLT

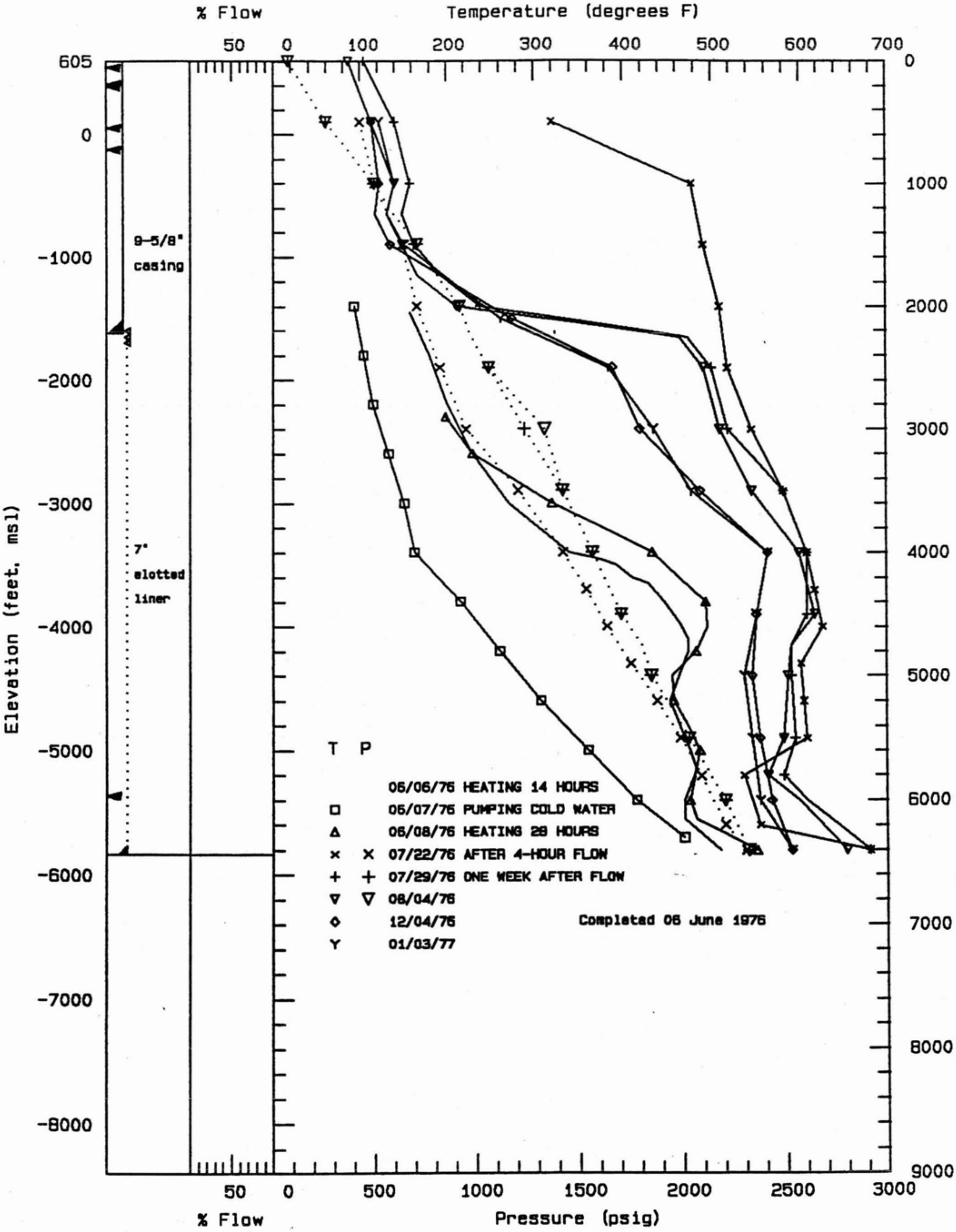
DOWNHOLE SUMMARY PLOT, WELL HGP-A



GeothermEx, Inc.

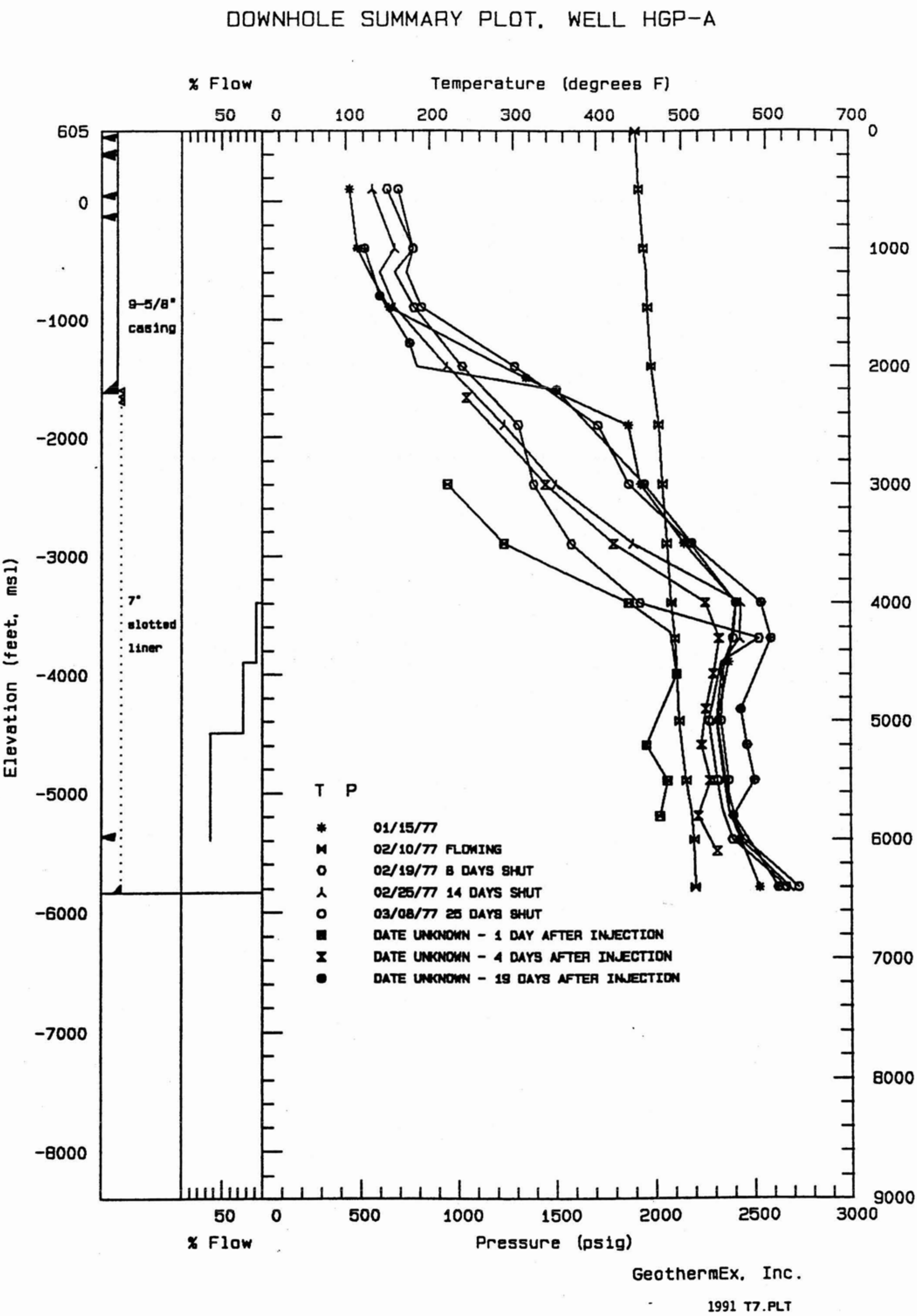
1991 T1.PLT

DOWNHOLE SUMMARY PLOT, WELL HGP-A

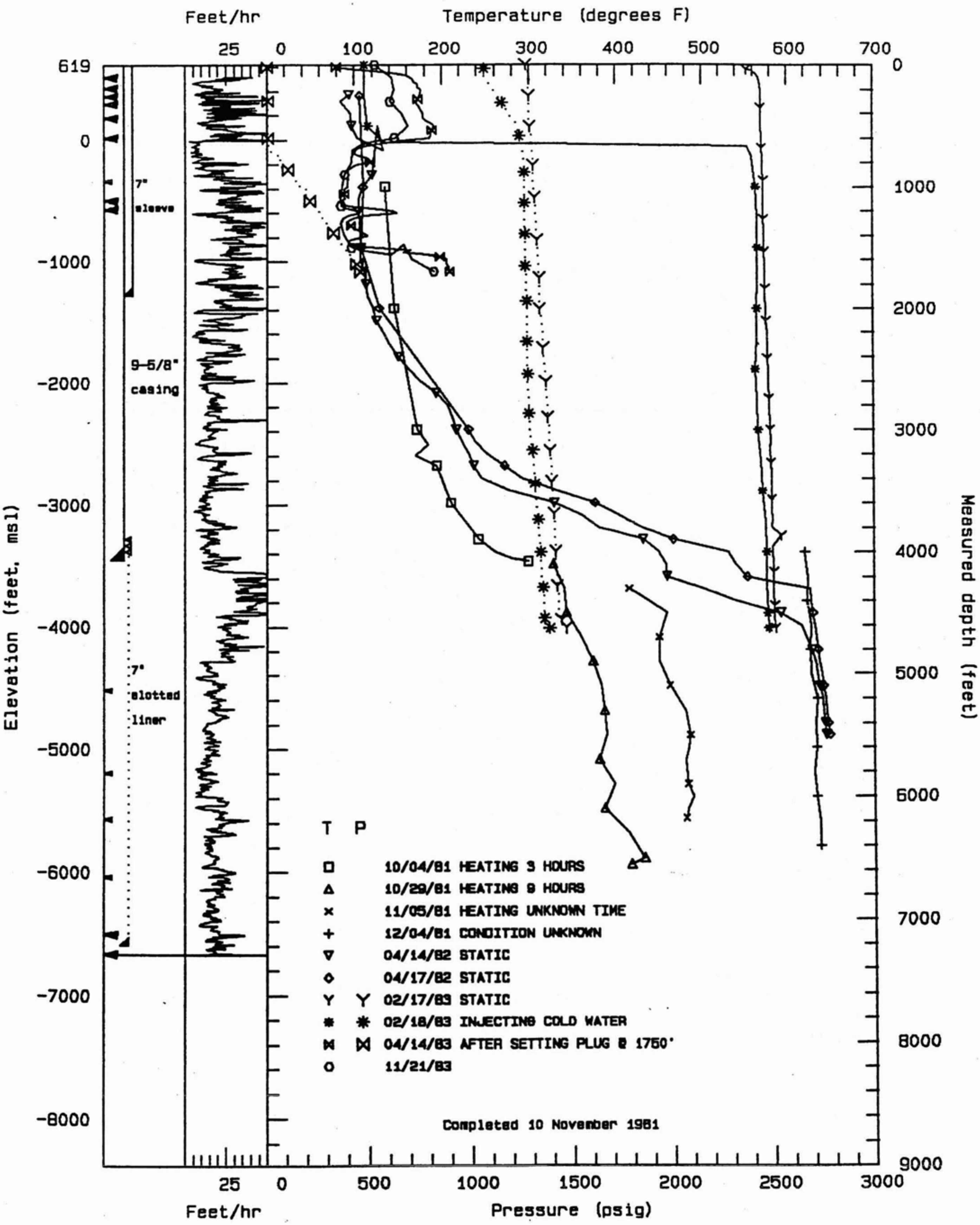


GeothermEx, Inc.

1991 T1.PLT


DOWNHOLE SUMMARY PLOT, WELL HGP-A
% Flow
Temperature (degrees F)
Elevation (feet, msl)
Measured depth (feet)
9-5/8" casing
7" slotted liner
T P
01/15/77
02/10/77 FLOWING
02/19/77 8 DAYS SHUT
02/25/77 14 DAYS SHUT
03/08/77 25 DAYS SHUT
DATE UNKNOWN - 1 DAY AFTER INJECTION
DATE UNKNOWN - 4 DAYS AFTER INJECTION
DATE UNKNOWN - 19 DAYS AFTER INJECTION
% Flow
Pressure (psig)
GeothermEx, Inc.
1991 T7.PLT

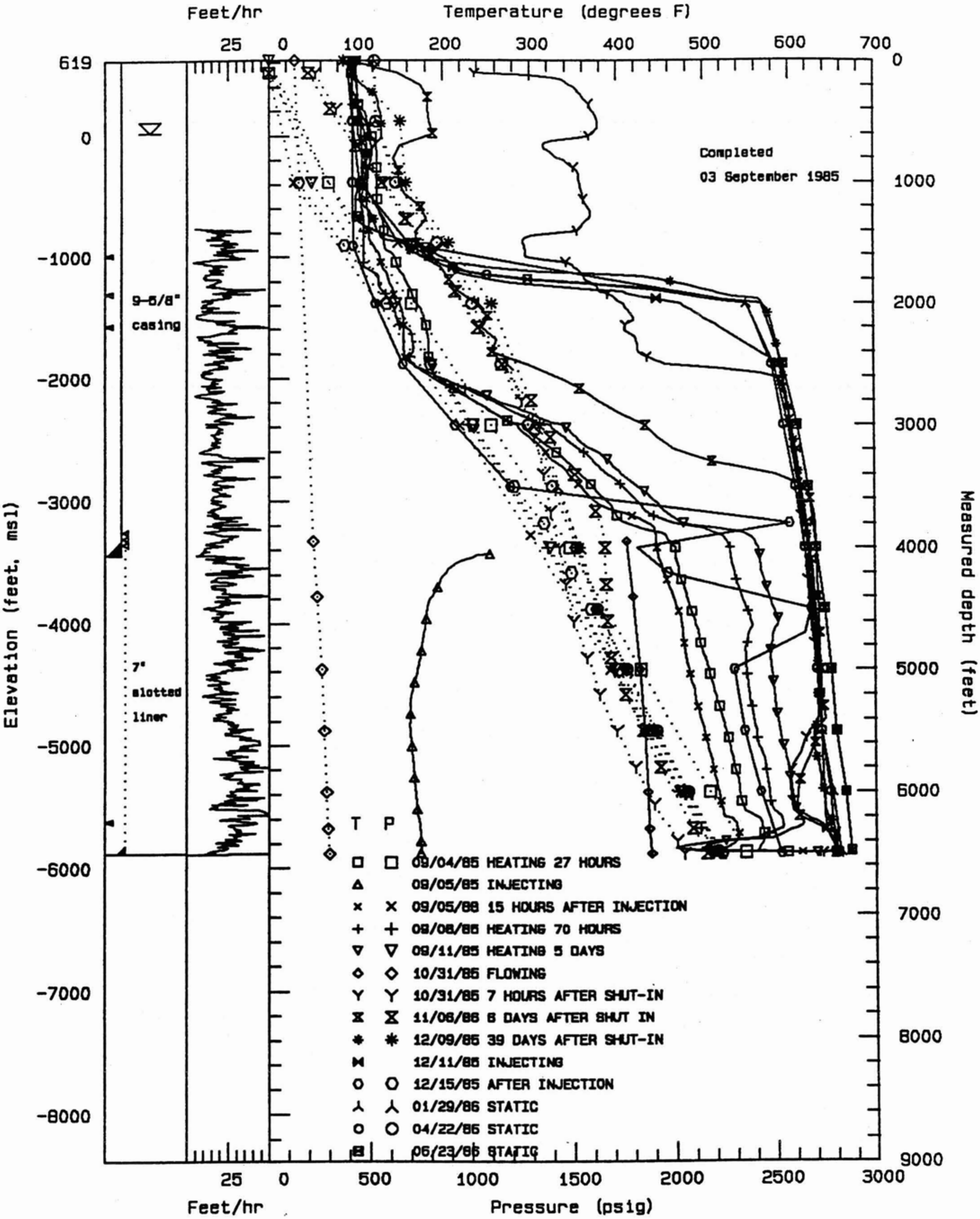
DOWNHOLE SUMMARY PLOT, WELL KS-1



GeothermEx, Inc.

1991 T1.PLT

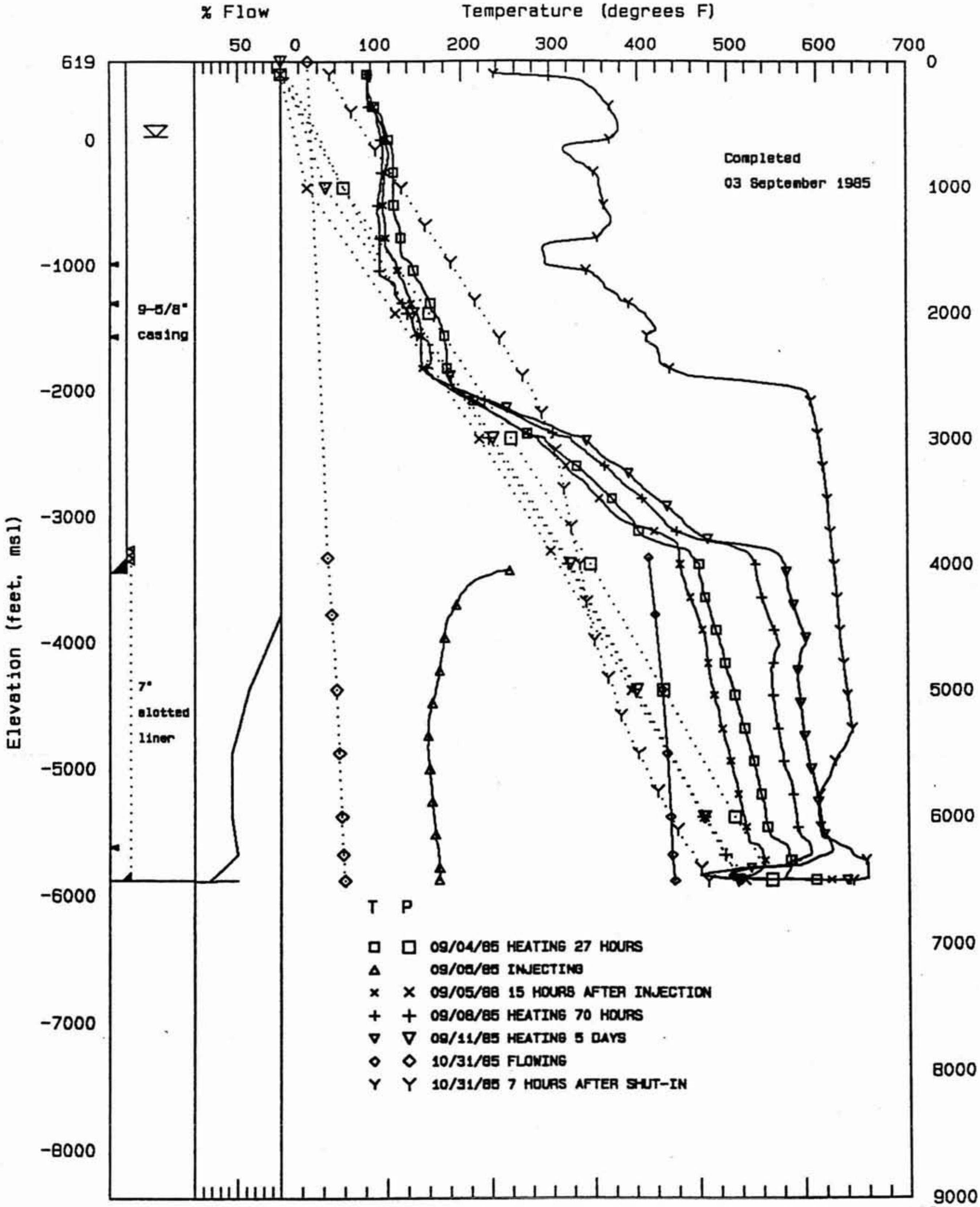
DOWNHOLE SUMMARY PLOT, WELL KS-1A



GeothermEx, Inc.

1991 KS1A27T.PLT

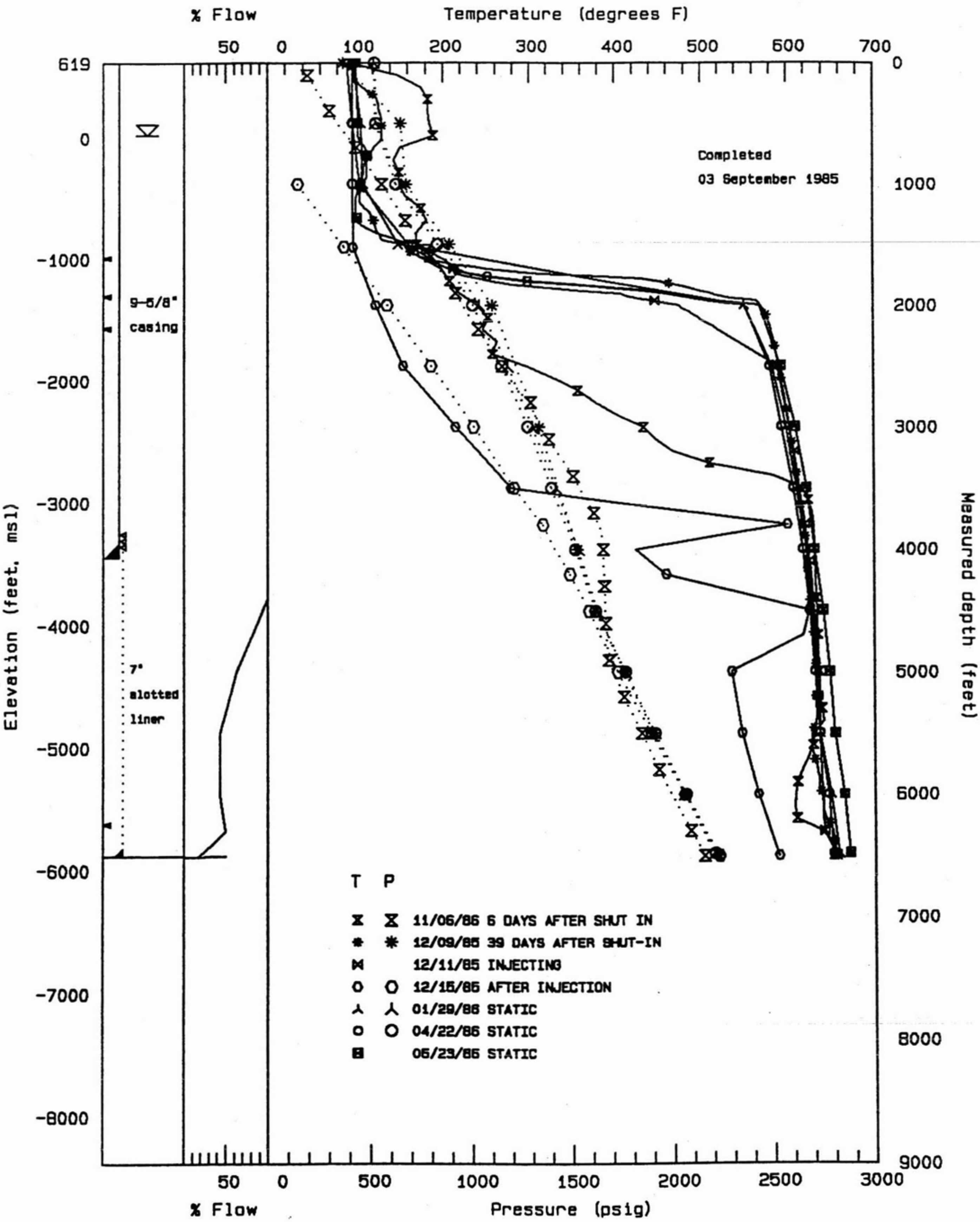
DOWNHOLE SUMMARY PLOT, WELL KS-1A



GeothermEx, Inc.

1991 KS1A27T.PLT

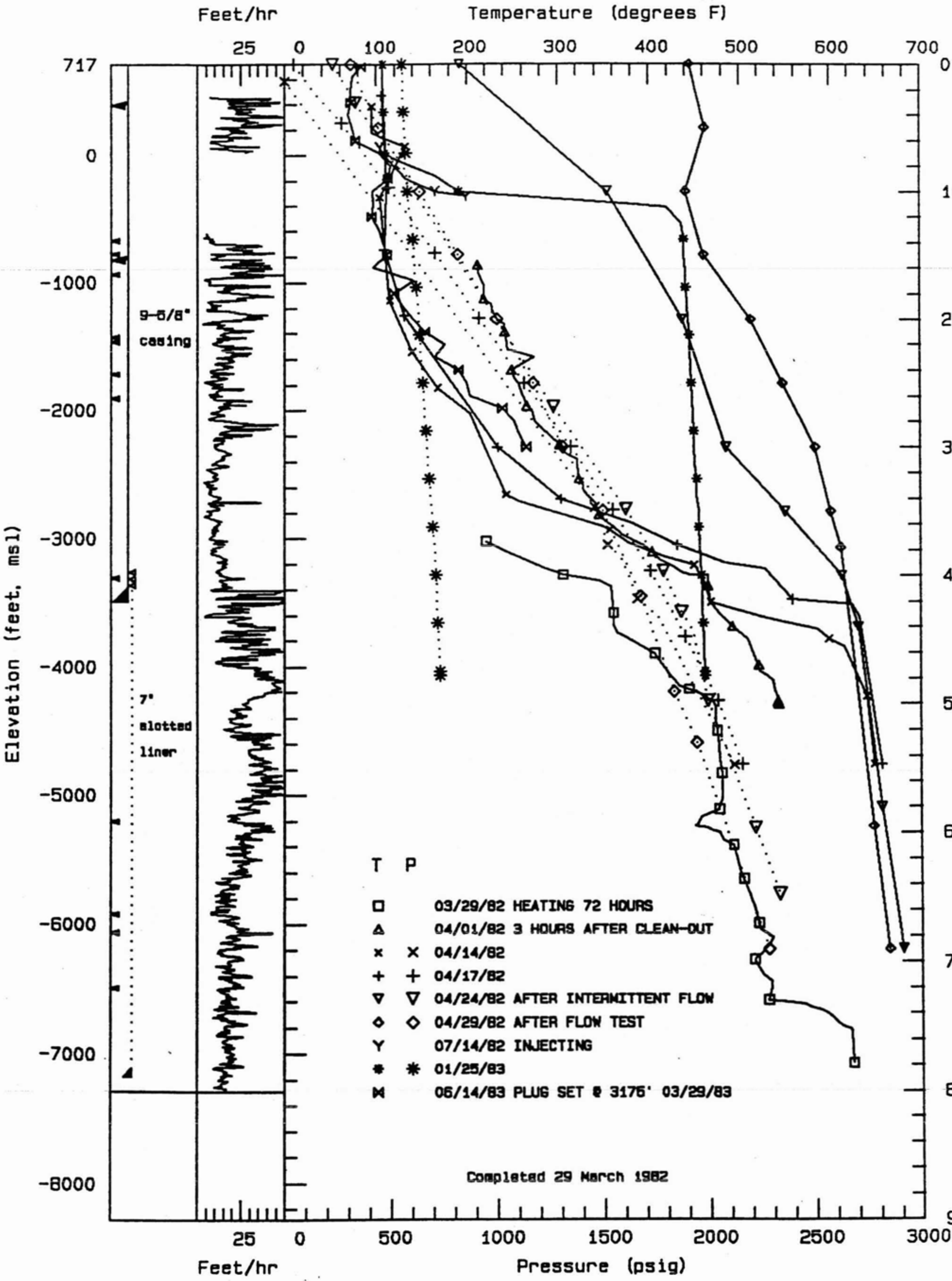
DOWNHOLE SUMMARY PLOT, WELL KS-1A



GeothermEx, Inc.

1991 T8.PLT

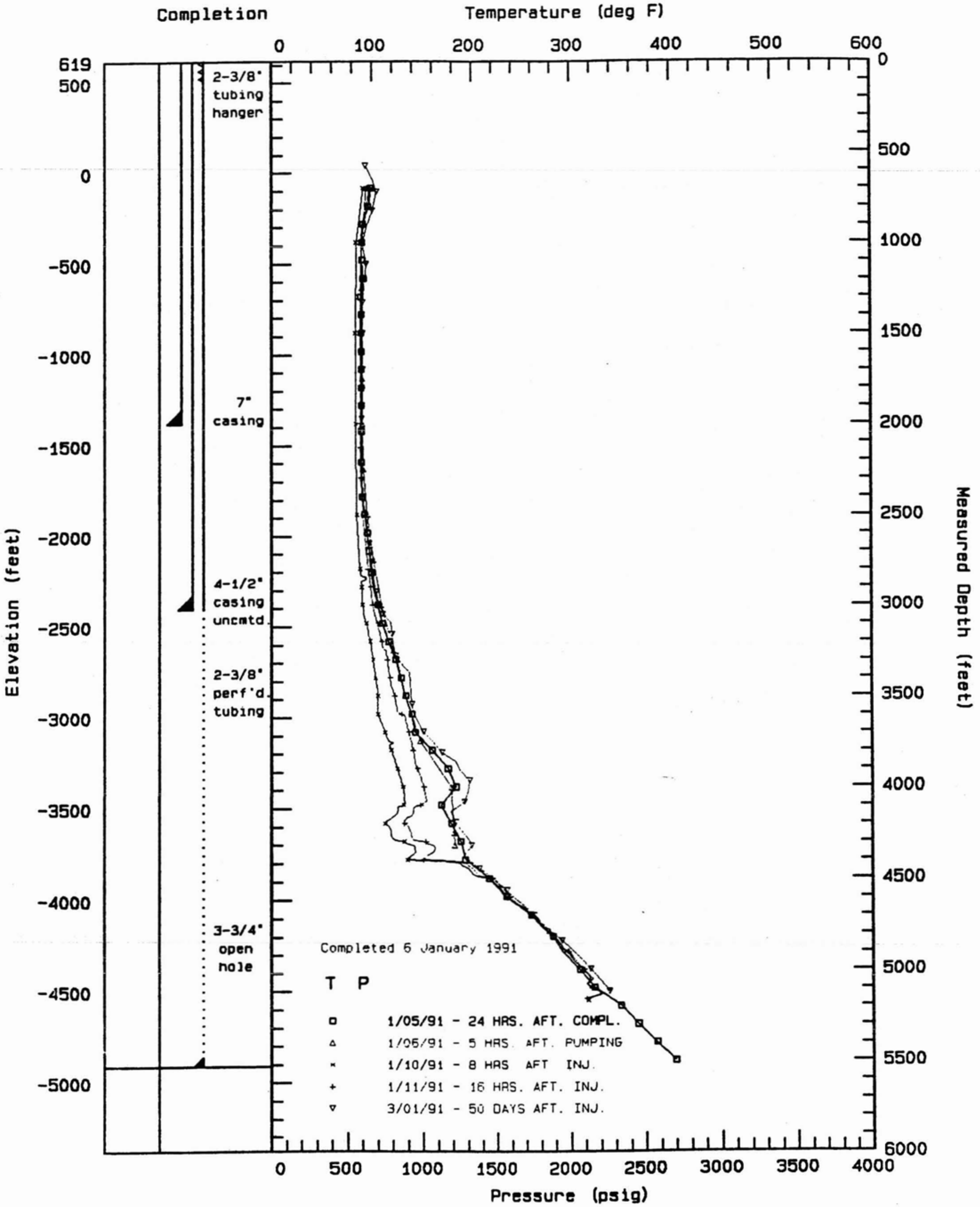
DOWNHOLE SUMMARY PLOT, WELL KS-2



GeothermEx, Inc.

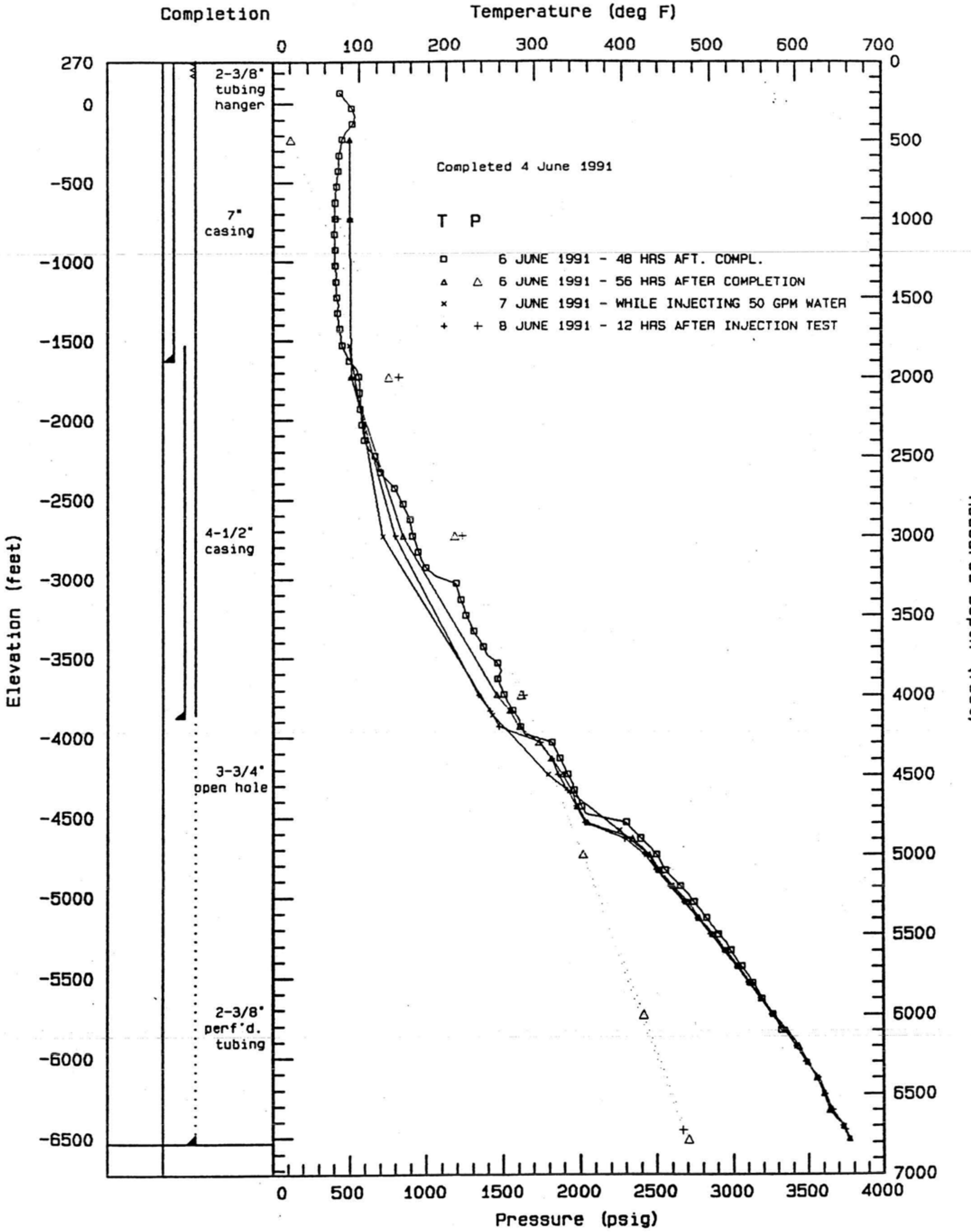
1991 KS2TO.PLT

DOWNHOLE SUMMARY PLOT - WELL SOH - 1



GeothermEx, Inc.

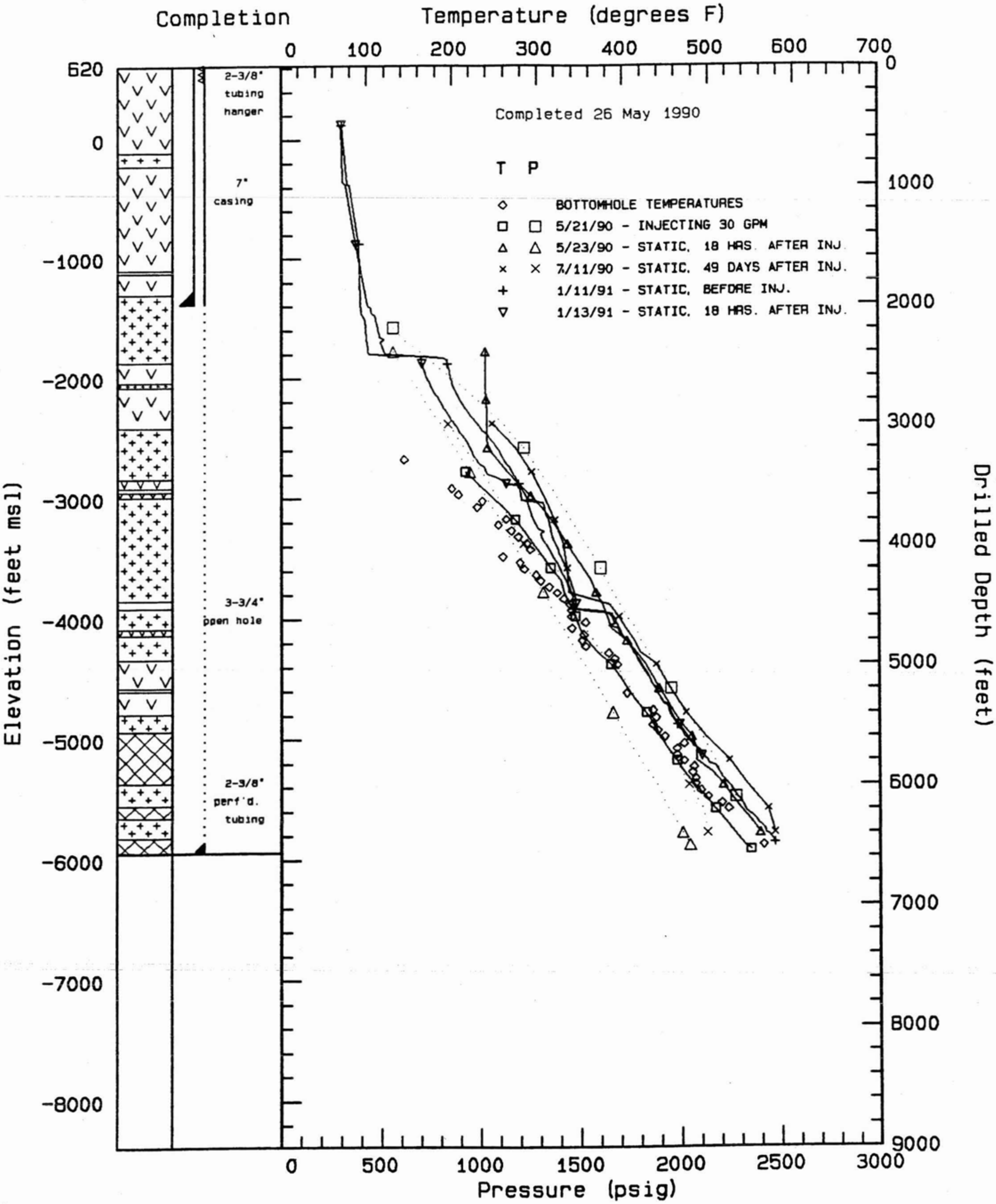
DOWNHOLE SUMMARY PLOT - WELL SOH - 2



GeothermEx, Inc.

10-11-1991 D: SOHUSGS.PLT

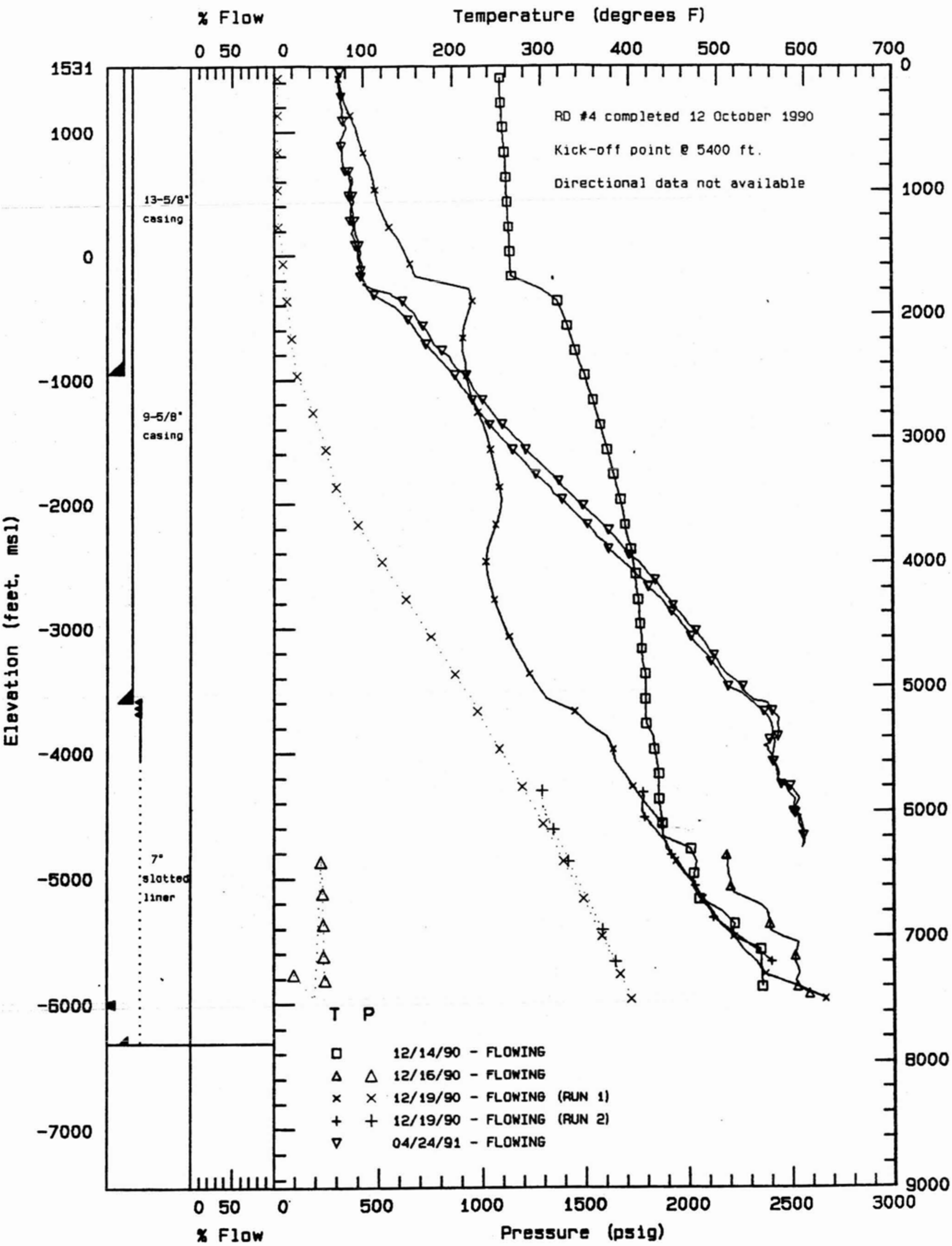
DOWNHOLE SUMMARY PLOT - HOLE SOH-4



GeothermEx, Inc.

07-23-1992 A:BHOLE.PLT

DOWNHOLE SUMMARY PLOT, WELL KMERZ A-1 RD 4



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